



# Cold Spray Technology for Repair of Magnesium Rotorcraft Components

***ESTCP Proposal 06-E-PP3-031***

## **Team:**

**ARL**

**Bruce Sartwell - Naval Research Laboratory**

**Yogi Kestler – NADEP Cherry Point**

**Tim Eden – ARL-PSU**

**Robert Guillemette SIK**

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# Cold Spray Technology for Repair of Magnesium Rotorcraft Components

## Program Objectives:

- To reclaim ZE 41A magnesium alloy components on Army and Navy helicopters that have been removed from service due to severe corrosion and/or wear.
- ARL will provide a repair/rebuild cold spray procedure for scrapped parts and assist in the transition and implementation of this technology, initially, at NADEP, Cherry Point, NC.



# Cold Spray Technology for Repair of Magnesium Rotorcraft Components



**Meeting Objective:** to lay the foundation for a JTP that can be executed by the ESTCP team such that at the completion of the program NADEP, Cherry Point has a fully functional cold spray system that is reclaiming magnesium rotorcraft components.

## •Overview of Cold Spray Technology

- Leveraged Programs ( **unprecedented head start**)
- Discuss ARL Capabilities and Advantages of Cold Spray

## •Present Test Results to Date

- Coating Integrity and Microstructural Analysis
- Adhesion, Hardness and Corrosion Tests
- Coating Material Selection and Powder Development
- Cold Spray Process Development and Hardware Modifications
- Cold Spray Demonstration on ZE 41A Mg Housings



# **Cold Spray Center at the US Army Research Laboratory (ARL) Aberdeen Proving Ground, MD 21005-5069**



## **ARL Cold Spray Research Team**

Phillip Leyman	Process Engineer	(410) 306-0818
Dr. Dennis Helfritch	Process Engineer	(410) 306-1928
Dr. Matthew Trexler	Materials Engineer	(410) 306-0808
Michael Lister	Materials Engineer	(410) 306-1592
Scott Grendahl	Materials Engineer	(410) 306-0819
Dr. William DeRosset	Modeling/Simulation	(410) 306-0816
Marc Pepi	Mechanical Engineer	(410) 306-0848
Victor Champagne	Team Lead/Materials	(410) 306-0822



# ARL Leveraged Formal Programs

*•to develop aluminum cold spray coatings for aluminum, magnesium and/or steel substrates have been established with the following:*

1. Defense Science & Technology Organization (DSTO)
2. Joint Strike Fighter (JSF)
3. National Center for Manufacturing Sciences (NCMS)
4. Lockheed Martin
5. Penn State Applied Research Laboratory
6. Lawrence Livermore National Labs (LLNL)
7. South Dakota School of Mines (SDSM)





# Overview of Cold Spray Technology



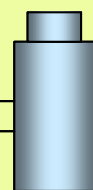
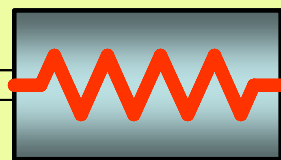
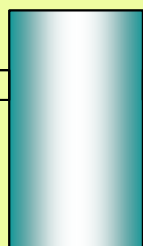
**Cold Spray:** a process by which particulates are deposited by means of ballistic impingement upon a suitable substrate at super sonic velocities to form a coating or a free-standing structure.

**Gas Control Module**

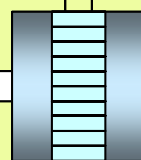
**Electric Heater**

**Cold Spray System Configuration**

$N_2$  or  
He gas



**Powder Feeder**



**Supersonic Nozzle**

**Particle Stream**

**Substrate**

**Deposit**

- Main Gas Stagnation Pressure 100-500 psi
- Gas Temperature 0-1300°F
- Main Gas Flow Rate 30-100 CFM
- Powder Feed Rate 10 to 30 pounds/hour
- Particle Velocity 300-1500 m/sec.
- Particle Size 1-100um diameter



# Cold Spray Advantages



## **Super Plastic Particle Agglomerate Mixing (SPAM) bond**

plastic deformation may disrupt thin oxide surface films to permit bonding similar to explosive welding

## **Compressive residual stresses**

particles “peen” surface

plasma and wire-arc thermal spray coatings tend to be in tension

## **High density**

low porosity:  $< 0.5 \%$

low oxide content  $< 0.3\%$

## **Thick coatings**

free-form fabrication

## **Low Temperature Application**

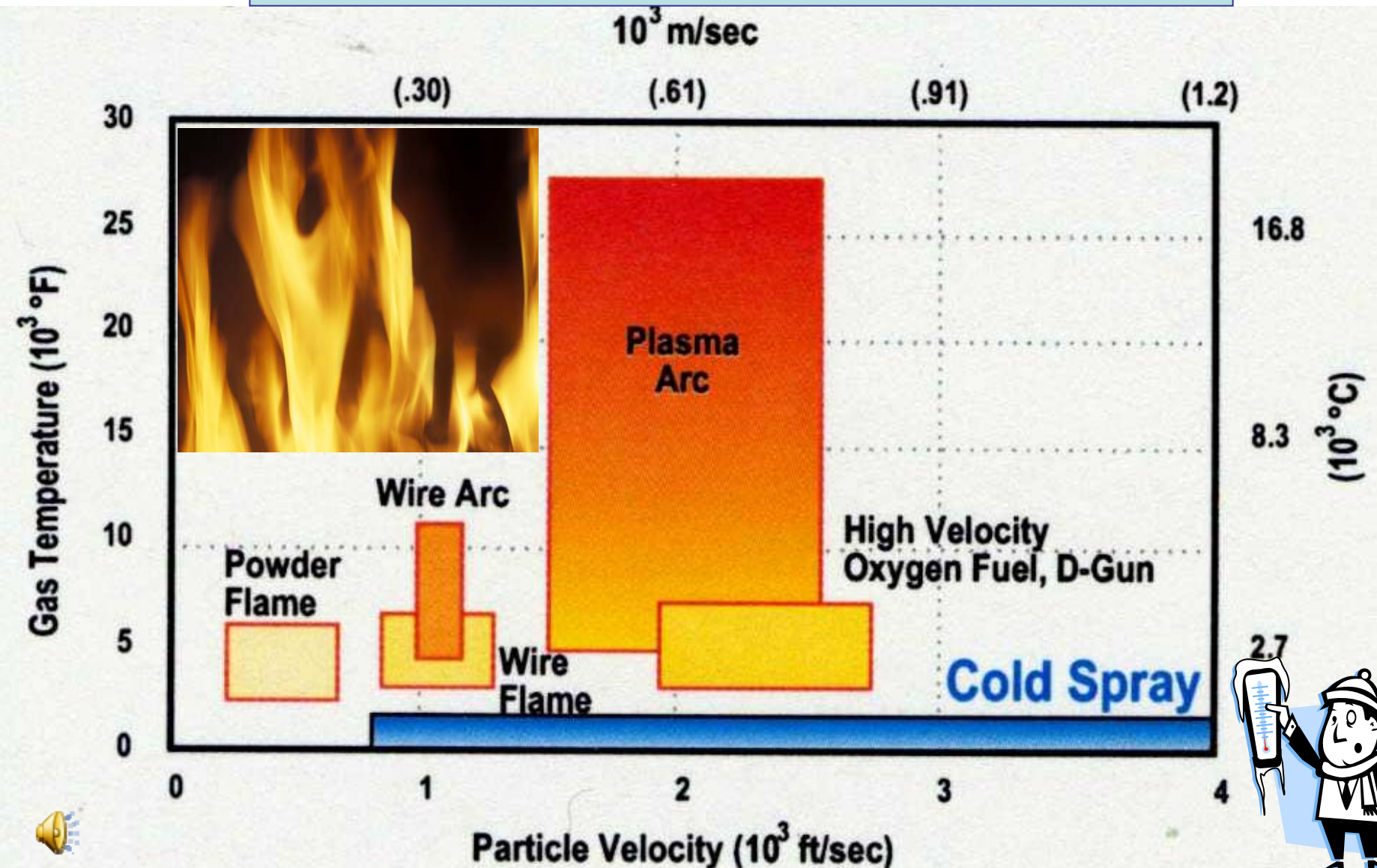
thermally sensitive substrates

low stresses due to CTE mismatch



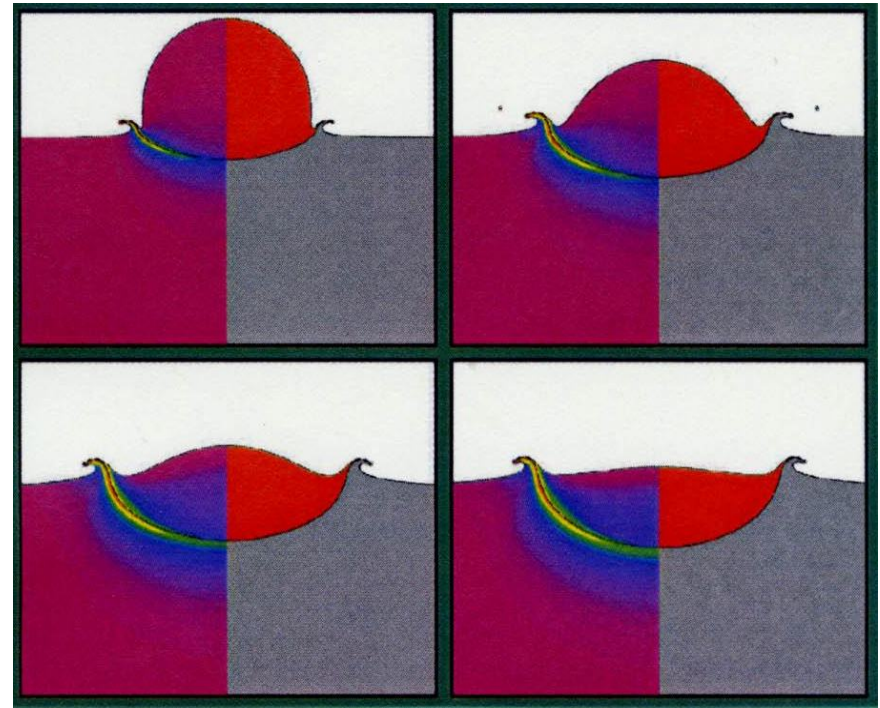
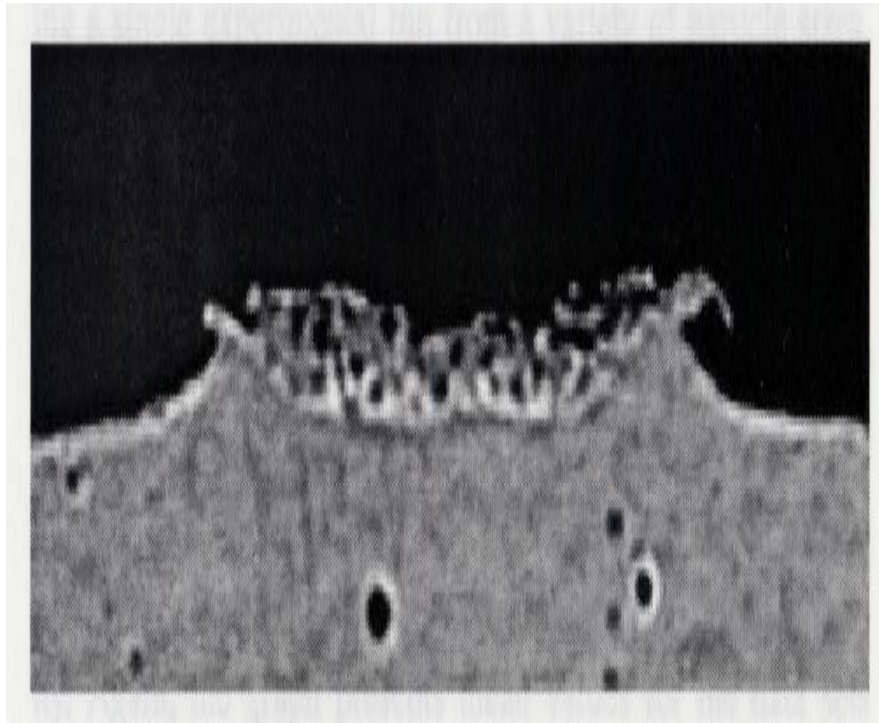


# Cold Spray vs. Thermal Spray



Cold Spray is performed at lower temperatures at high particle velocities

# Copper Particle Impact Site

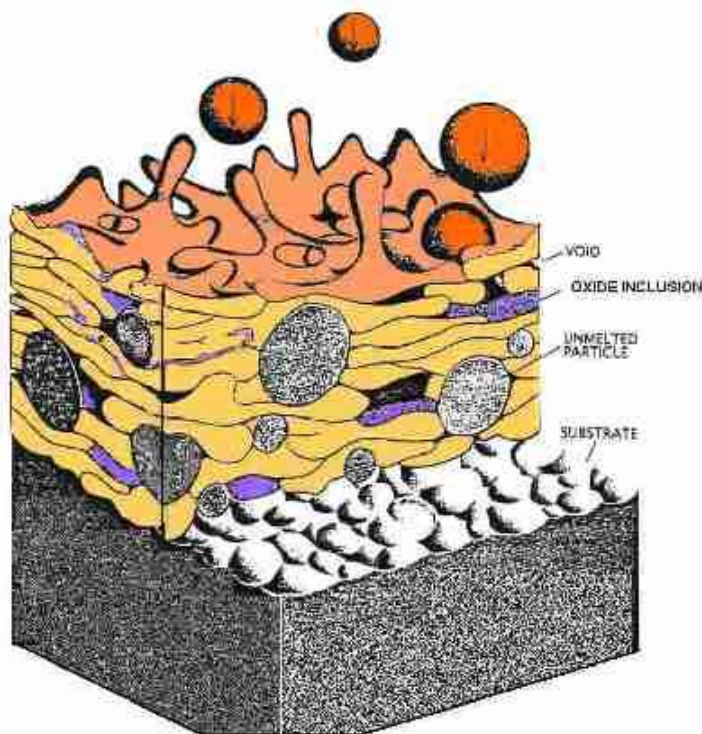


**Cross section of the impact site between a copper particle and a stainless steel substrate.**



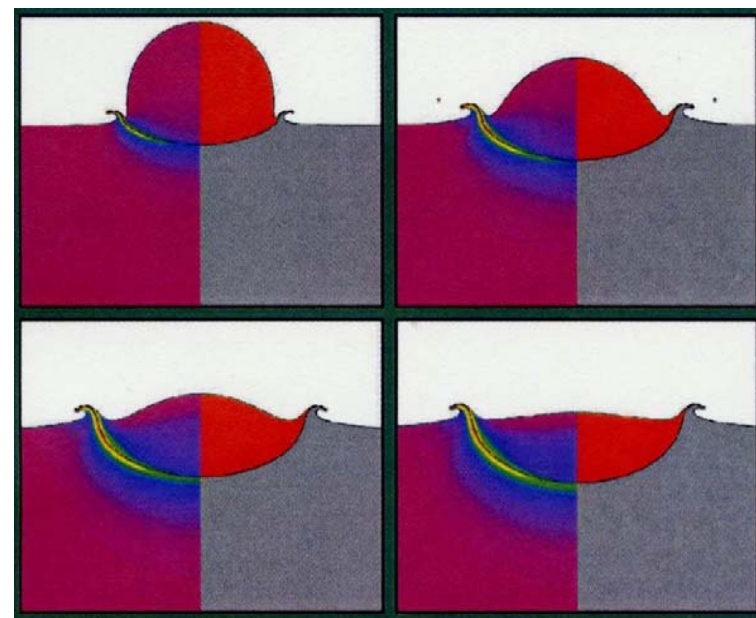
# Advantages of Low Temperature Process

## Thermal Spray



[www.gordonengland.co.uk](http://www.gordonengland.co.uk)

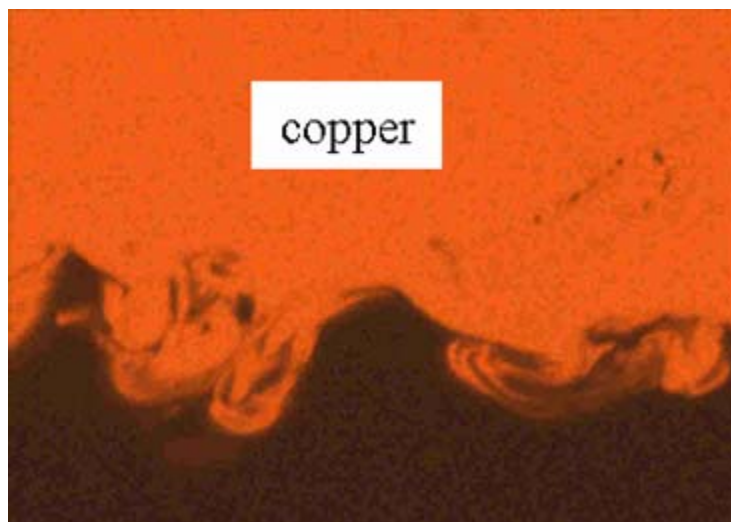
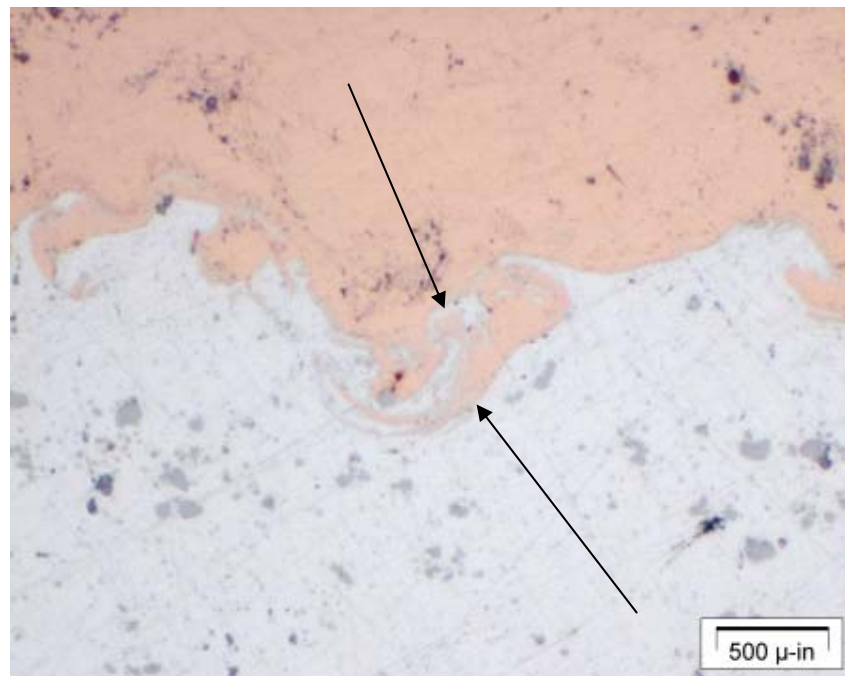
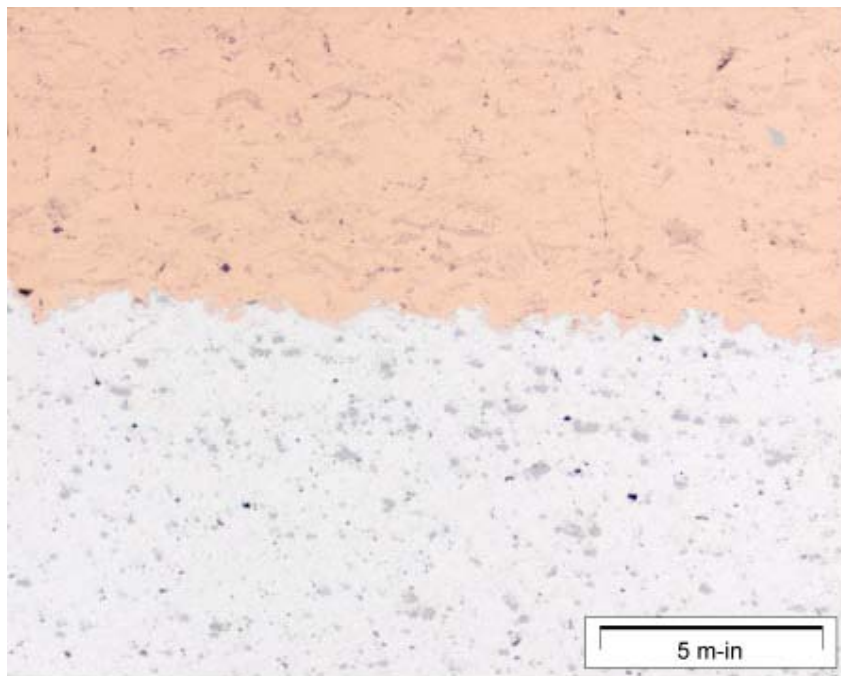
## Cold Spray



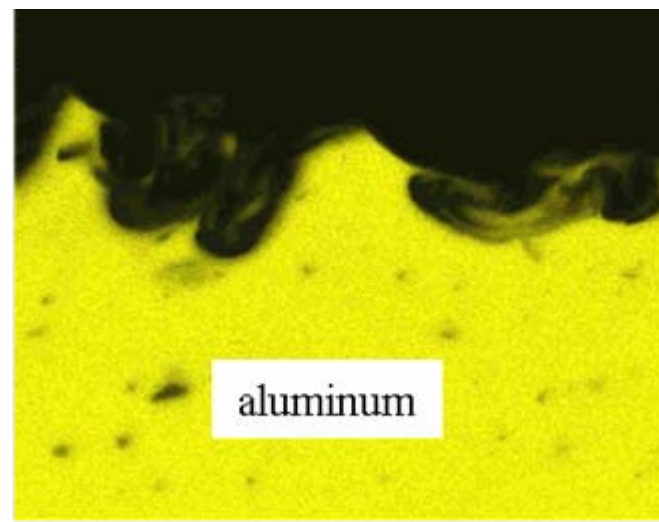
The melting of particles that occurs during most thermal spray processes can result in oxidation of both the coating and substrate materials. The resulting oxides decrease the adhesive and cohesive strengths of the coating. The cold spray process avoids such reactions.



# Mechanical Mixing at Interface

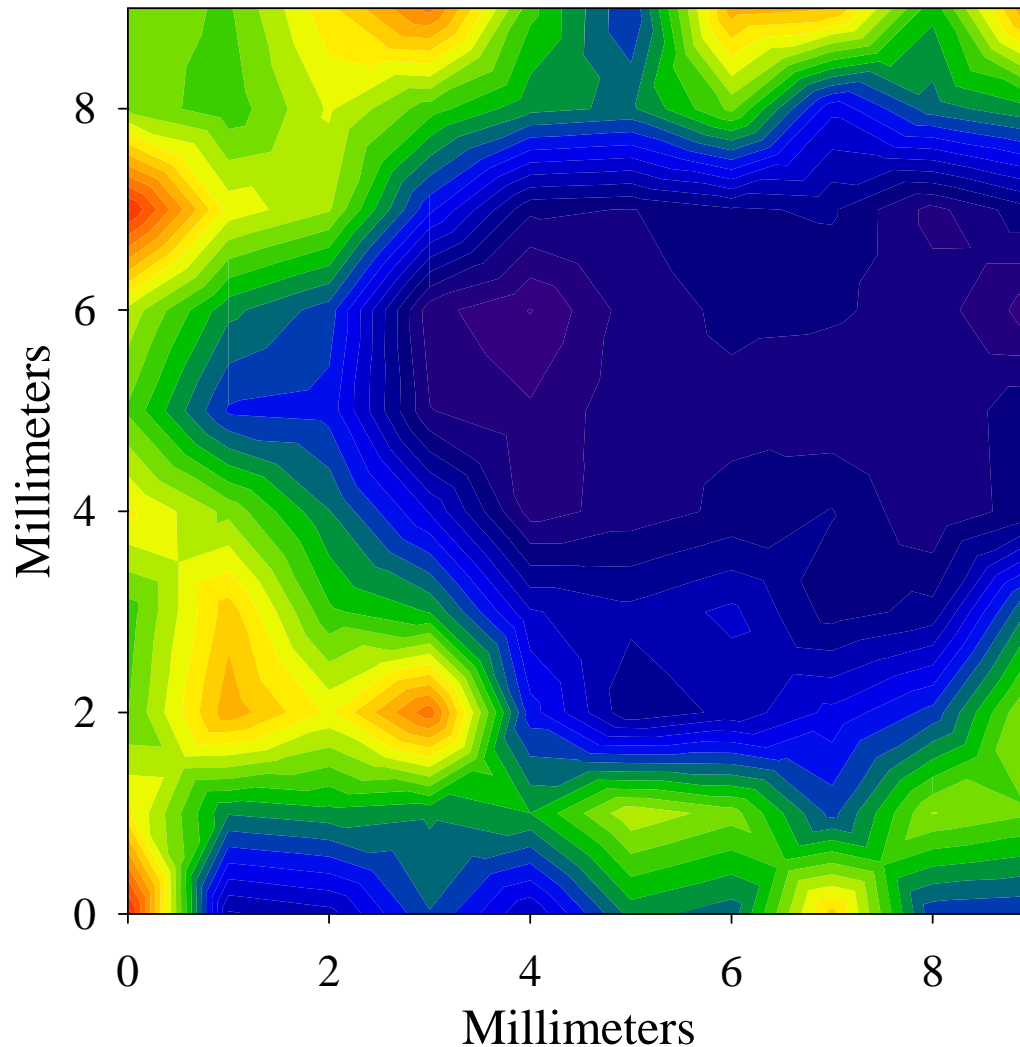


EDS X-ray Mapping  
showing mechanical  
mixing between  
coating material and  
substrate

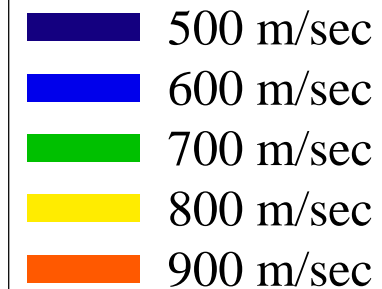




# Particle Velocity Distribution Measured by DPV 2000



**20 micron copper particles  
25 mm downstream  
400 psi, 400 C N<sub>2</sub> gas**





# Cold Spray Coating of Nickel On 6061-T6 Al



**Nickel  
Coating**

**100% Dense**



**Cold Spray Ni has a hardness of HRC 41 and a resistivity of 6.84uohm/cm**

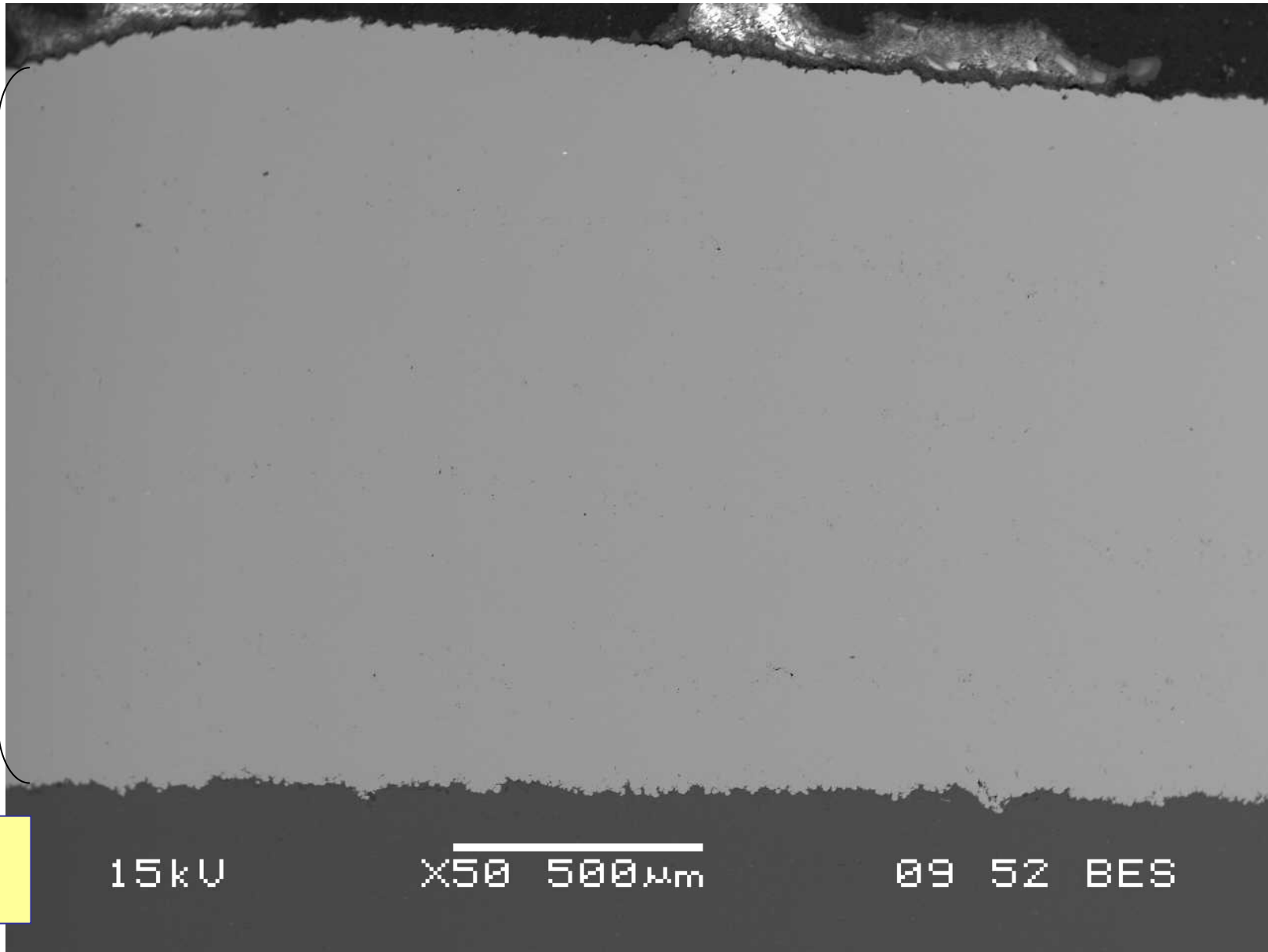




# 316L SS Deposited by the Stationary System Using He



316L SS  
Cold  
Spray  
Coating



Aluminum  
Substrate

15kV

X50 500 μm

09 52 BES



# Stationary Cold Spray System at ARL



**Robot-Controlled, High Pressure, He and N Gas**

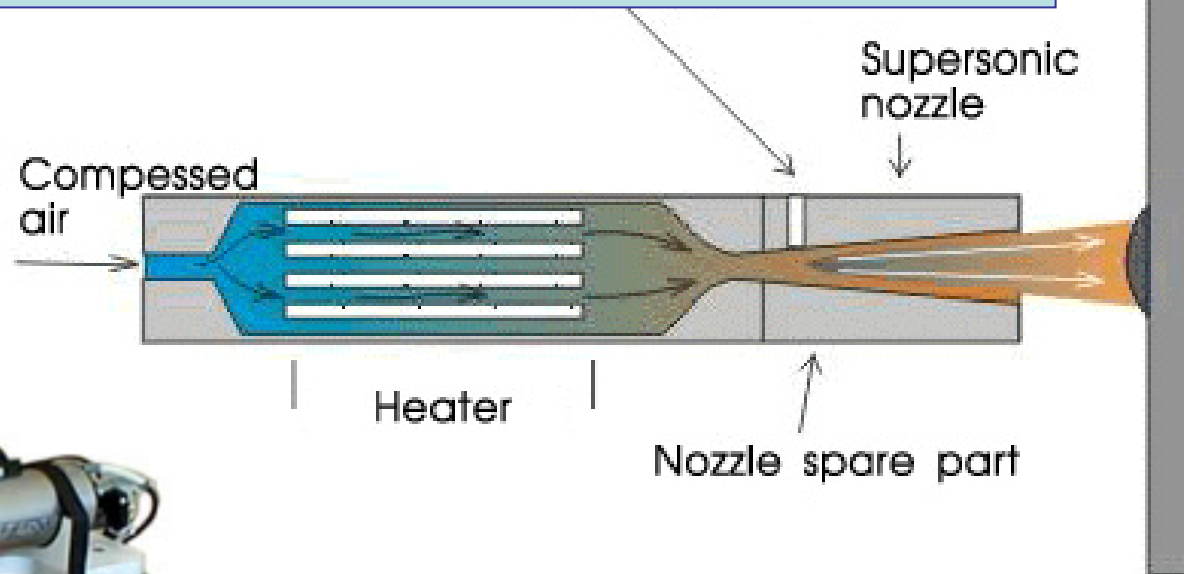


Main Gas Stagnation Pressure 100-500 psi   Gas Temperature 0-1300°F   Main Gas Flow Rate 30-100 CFM

Powder Feed Rate 10 to 30 pounds/hour

Particle Velocity 300-1500 m/sec.

# Portable Cold Spray Systems at ARL



- Hand-Held Heater-Nozzle
- Shop Compressed Air
- Particle Velocity 300-500 m/s



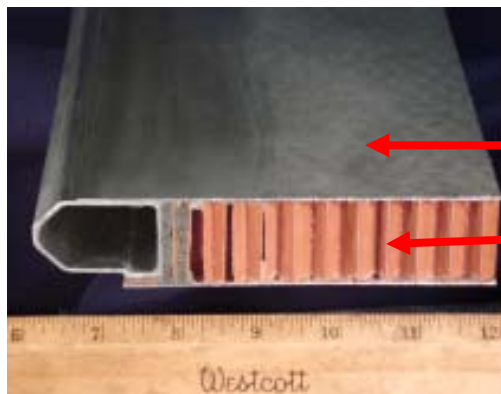
# EMI Shielding for HMMWV Shelter by Cold Spray

**ARL Produces First Prototype Using Cold Spray Technology for the Terminal High Altitude Area Defense (THAAD) Project Office.**



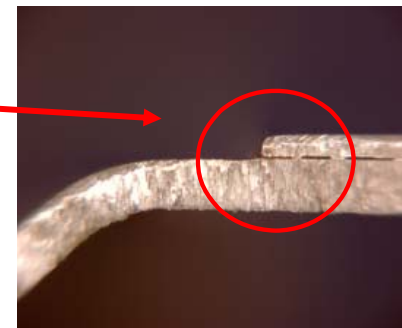
- HMMWV shelters require EMI shielding to prevent entrance/escape of electronic signals.
- The joints in al-composite walls must be sealed with a non-porous, conducting metal.
- The composite structure requires low-temperature application of sealer.

Conductive material needed to fill seams



Aluminum

Composite



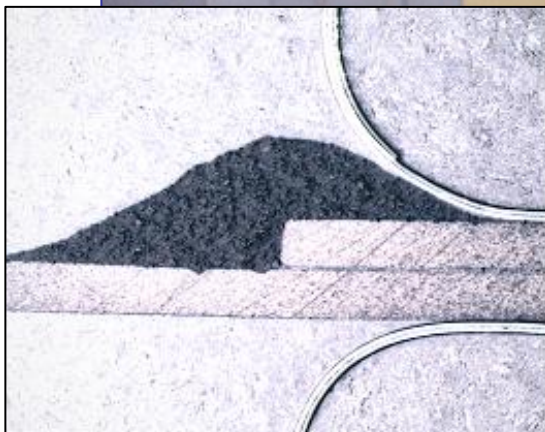




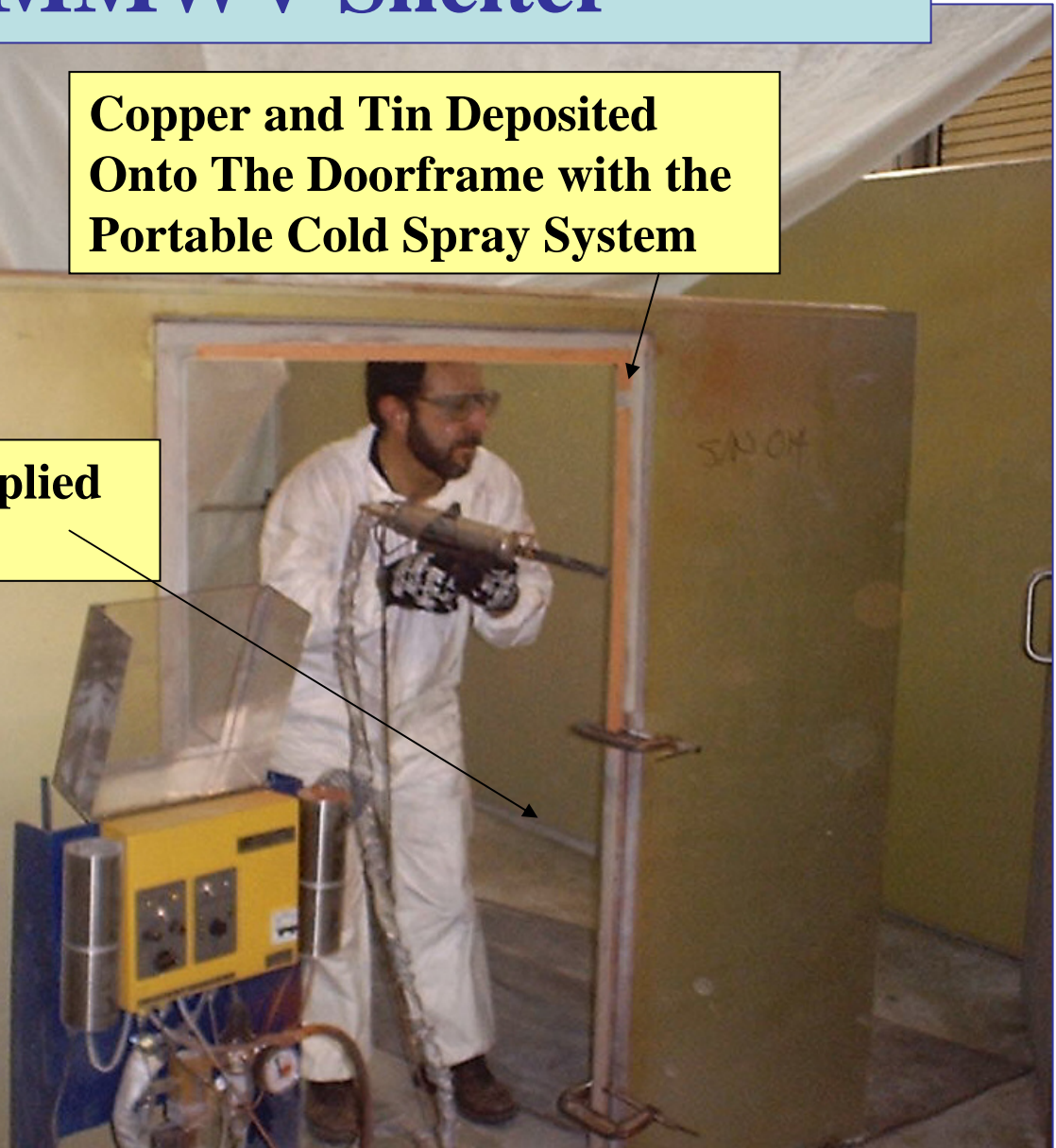
# Applying EMI Shielding on the HMMWV Shelter

**Copper and Tin Deposited  
Onto The Doorframe with the  
Portable Cold Spray System**

**Aluminum/Zinc Applied  
to Interior Seams**



**Cross Section of Cold  
Spray Coating**

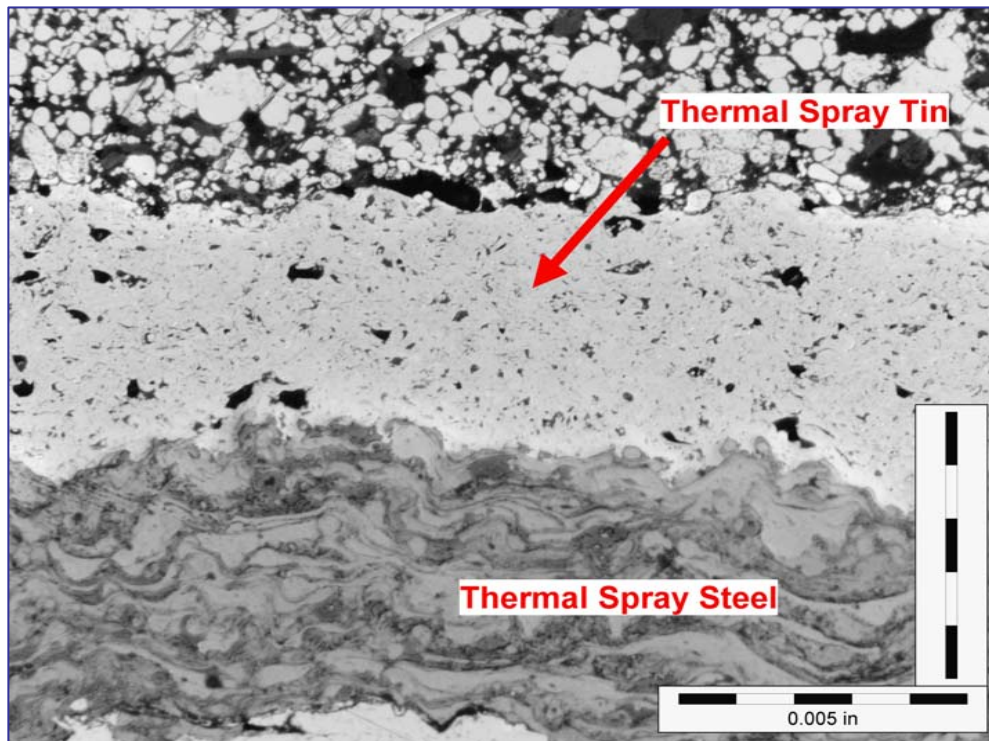




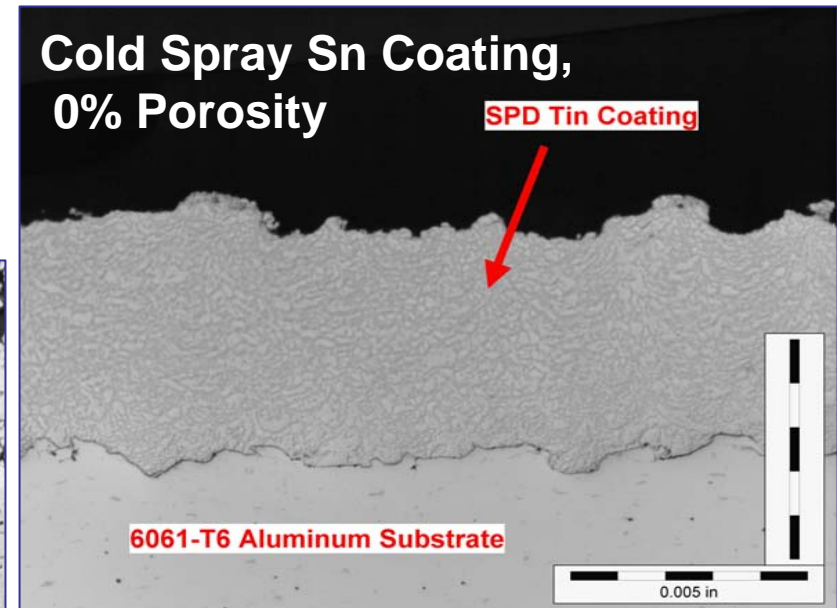
# Cold Spray vs. Thermal Spray



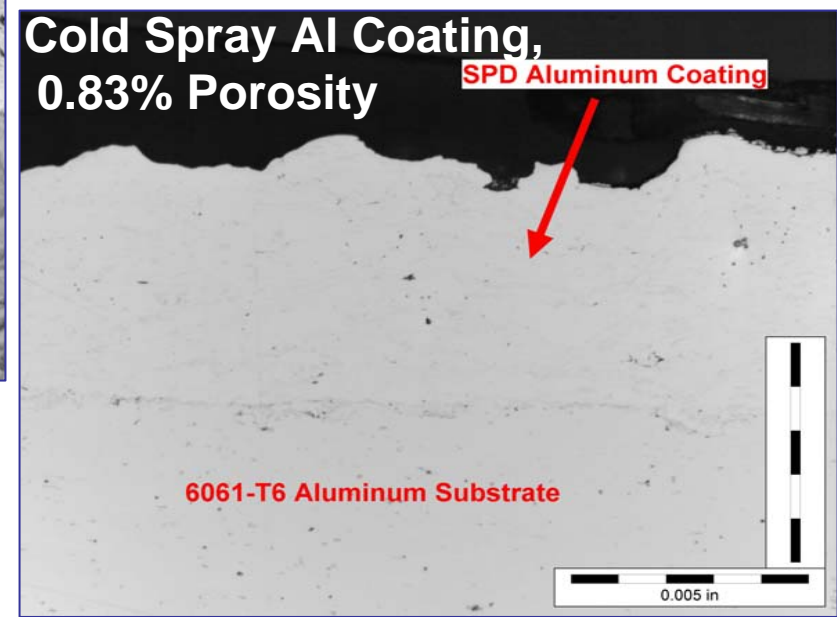
**Flame Spray Sn & Steel  
Coating, 12.2% Porosity**



**Cold Spray Sn Coating,  
0% Porosity**



**Cold Spray Al Coating,  
0.83% Porosity**







# **CTMA\*-NCMS\*\* Collaborative Project**

- 1. Corrosion protection of ferrous materials**
  - Painted structures – viz. ALV – access cover (USMC)
  - Hardened steel landing structures (Boeing)
  - Iron brake components (Delphi)
- 2. Corrosion protection and restoration of magnesium**
  - Repair ZE41& AZ91-D Magnesium (U.S. Army Research Lab, NADEP–Cherry Point, Ford)
- 3. Corrosion protection and restoration of aluminum**
  - repair of Alclad (Boeing commercial, Air logistics, Cherry Point)
- 4. Aluminum brazements (Delphi)**
- 5. Cold-spray consolidation by Ultrasonics (Solidica)**

\* Commercial Technologies for Maintenance Activities

\*\* National Center for Manufacturing Sciences



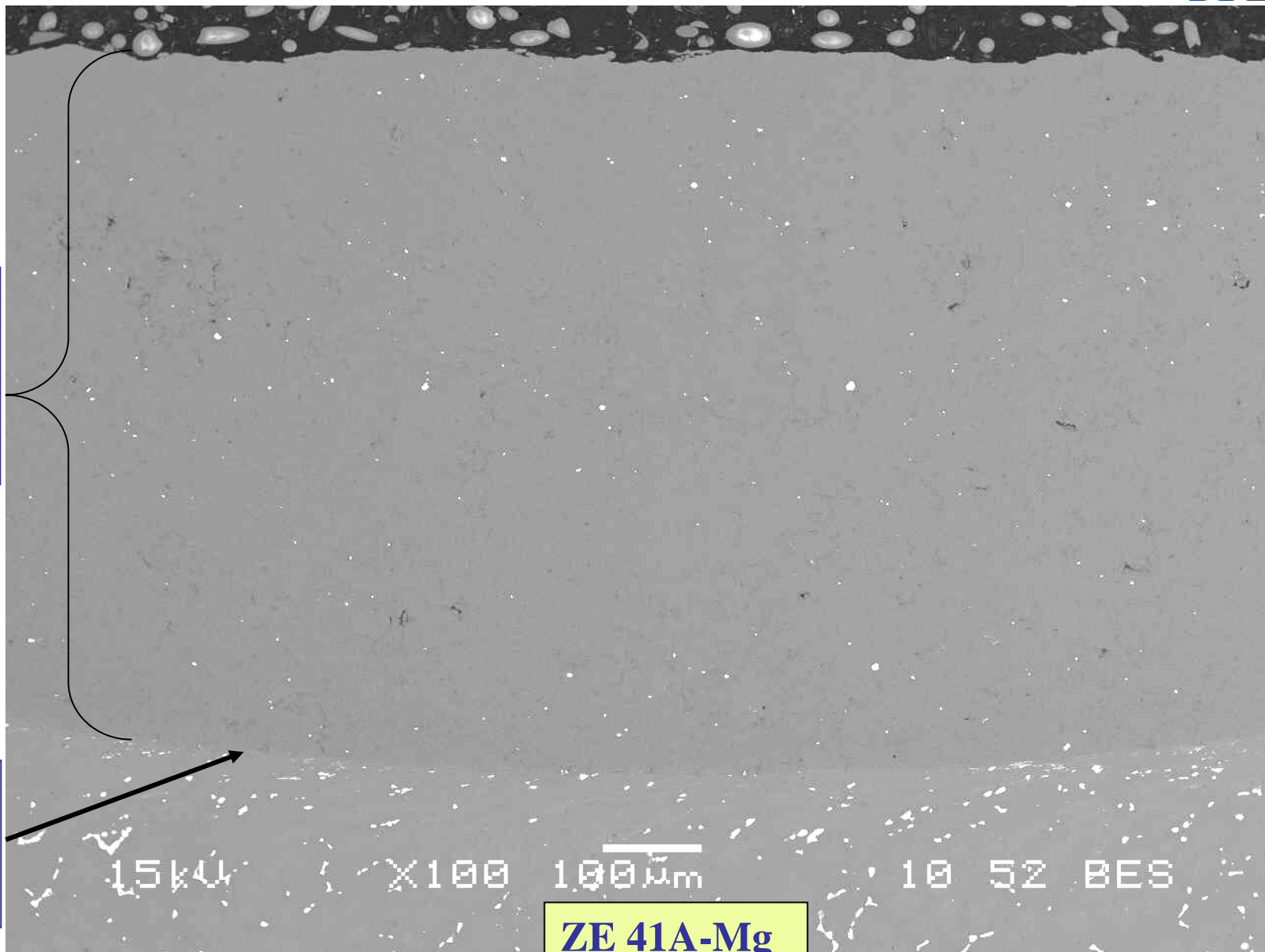
# Cold Spray Coating of CP-Al On ZE 41A-Mg



**Cold  
Spray  
CP- Al  
Coating**

**~100%  
Dense**

**Coating /  
Substrate  
Interface**



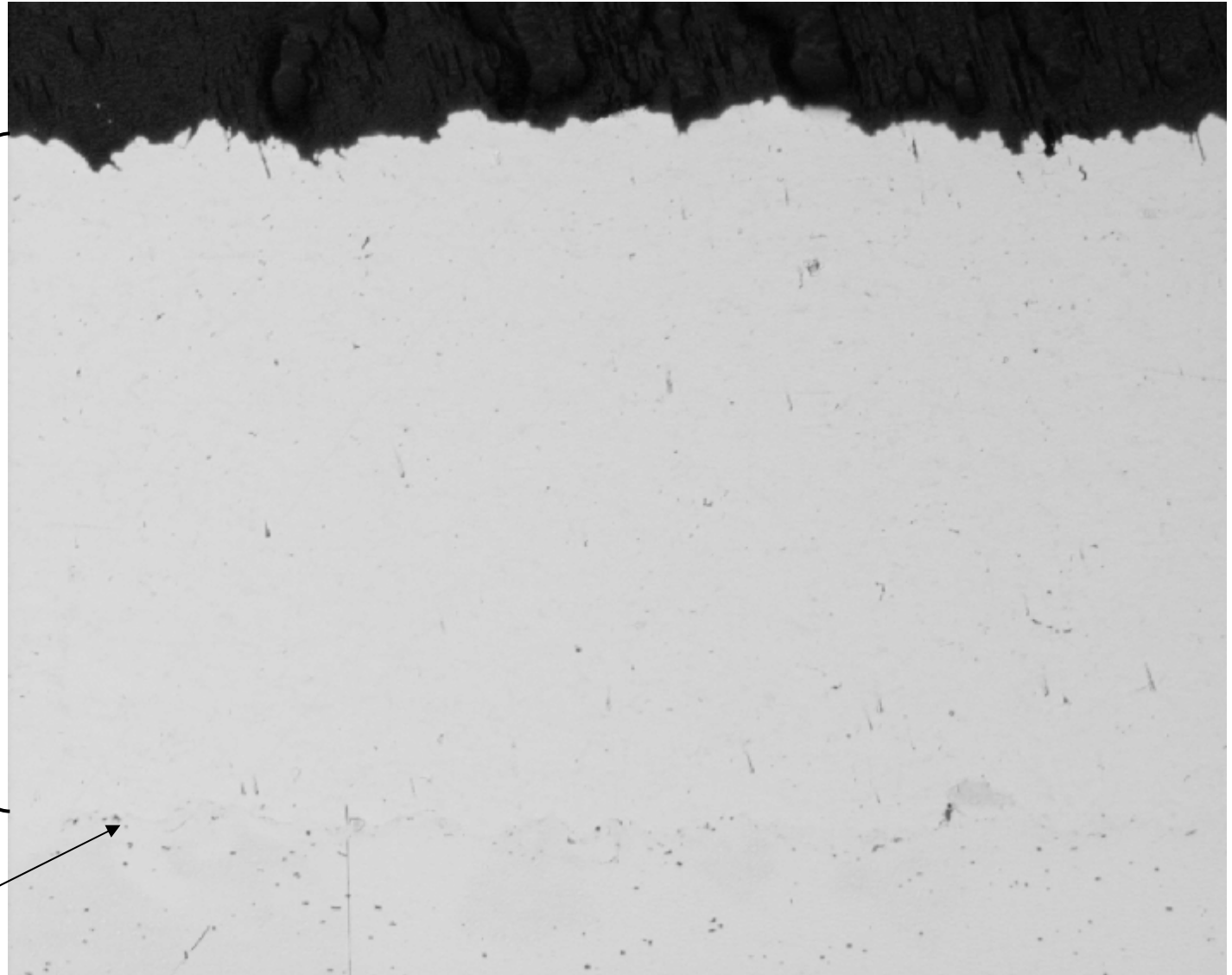


# CP- Al Cold Spray Coating Applied to ZE 41AMg

**Cold  
Spray Al  
Coating  
0.015 inch**

**8,500 psi  
adhesion**

**Interface is  
free of voids  
and oxides**





# CP- Aluminum Cold Spray Coating Adhesion to Magnesium

Program	Conditions	Adhesion (psi)
ARL-DSTO	N <sub>2</sub> , 380 psi, 250°C	2743
ARL-DSTO	He, 380 psi, 20°C	>6527
ARL-NCMS	He, 380 psi, 20°C	>8505

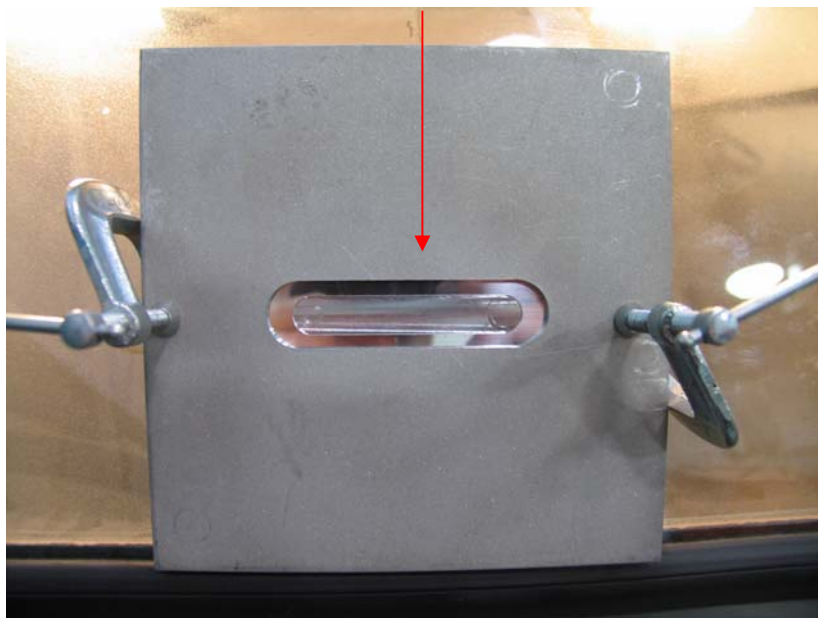
New Data Generated FY07 for ESTCP

ARL-ESTCP	N <sub>2</sub> , 380 psi, 400°C	>10,350
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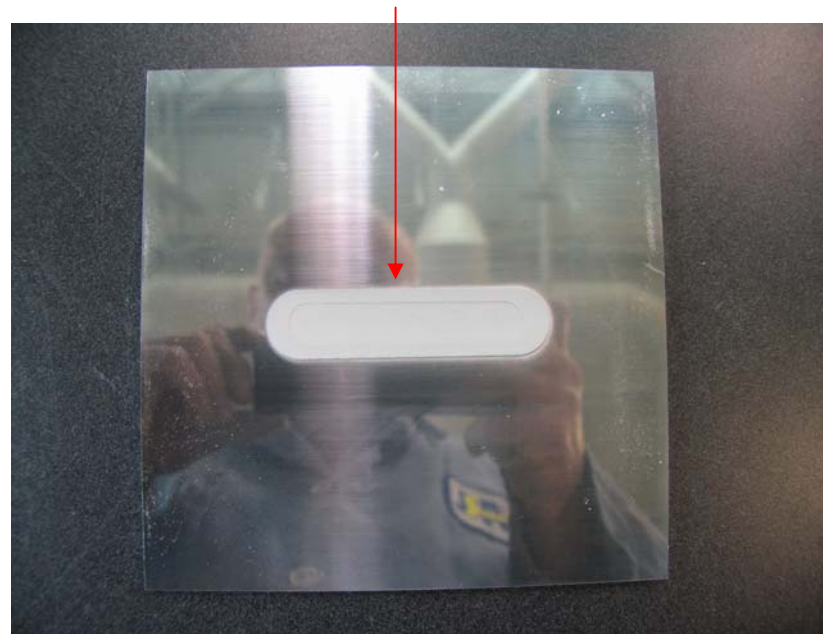
# Repair of Alclad Aircraft Skin by Cold Spray using CP Aluminum

**Machined slot**



**Template shielded before spray**

**Cold Spray CP Al**



**0.035 inch thick cold spray repair**





# Example of Damage Repair

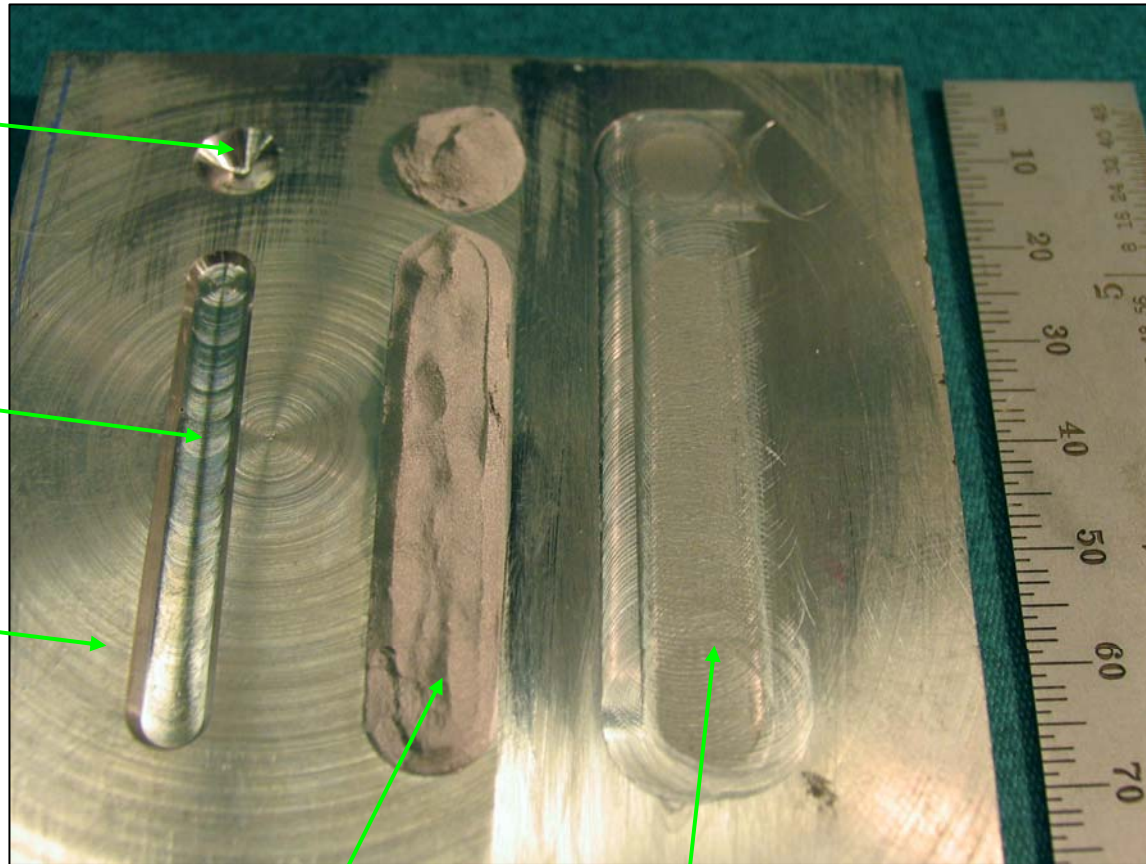
**Machined Pit**

**Machined Groove**

**ZE 41A  
Magnesium Plate**

**CP-Aluminum Cold Spray Coating**

**Machined Flush**





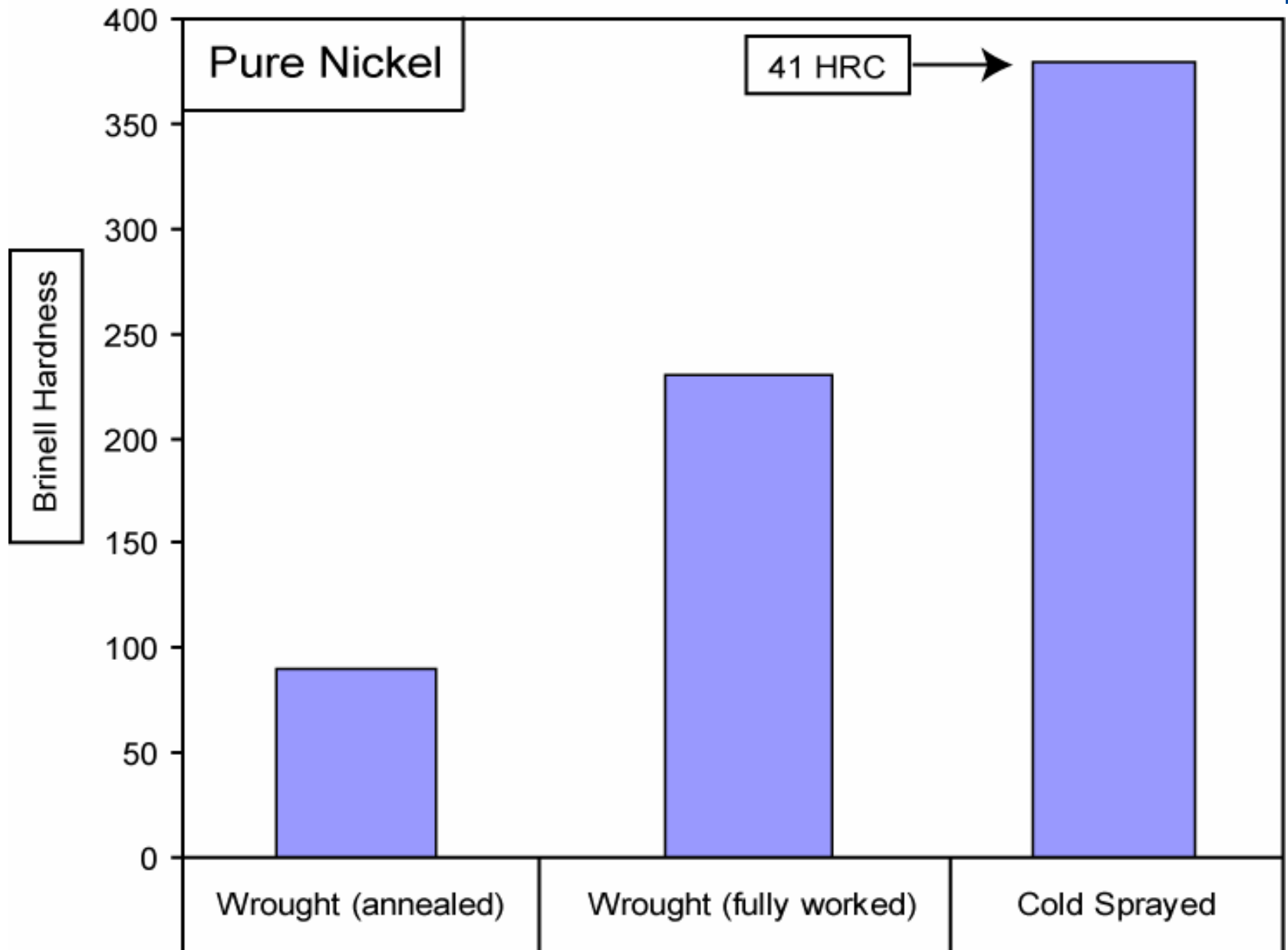


# **Cold Sprayed vs. Wrought Materials Hardness Comparison**

- The hardness of a cold-sprayed material is significantly higher than that of a conventional wrought material.**
- The hardening is a result of the plastic deformation that occurs during particle impact and the refined microstructure of the material.**

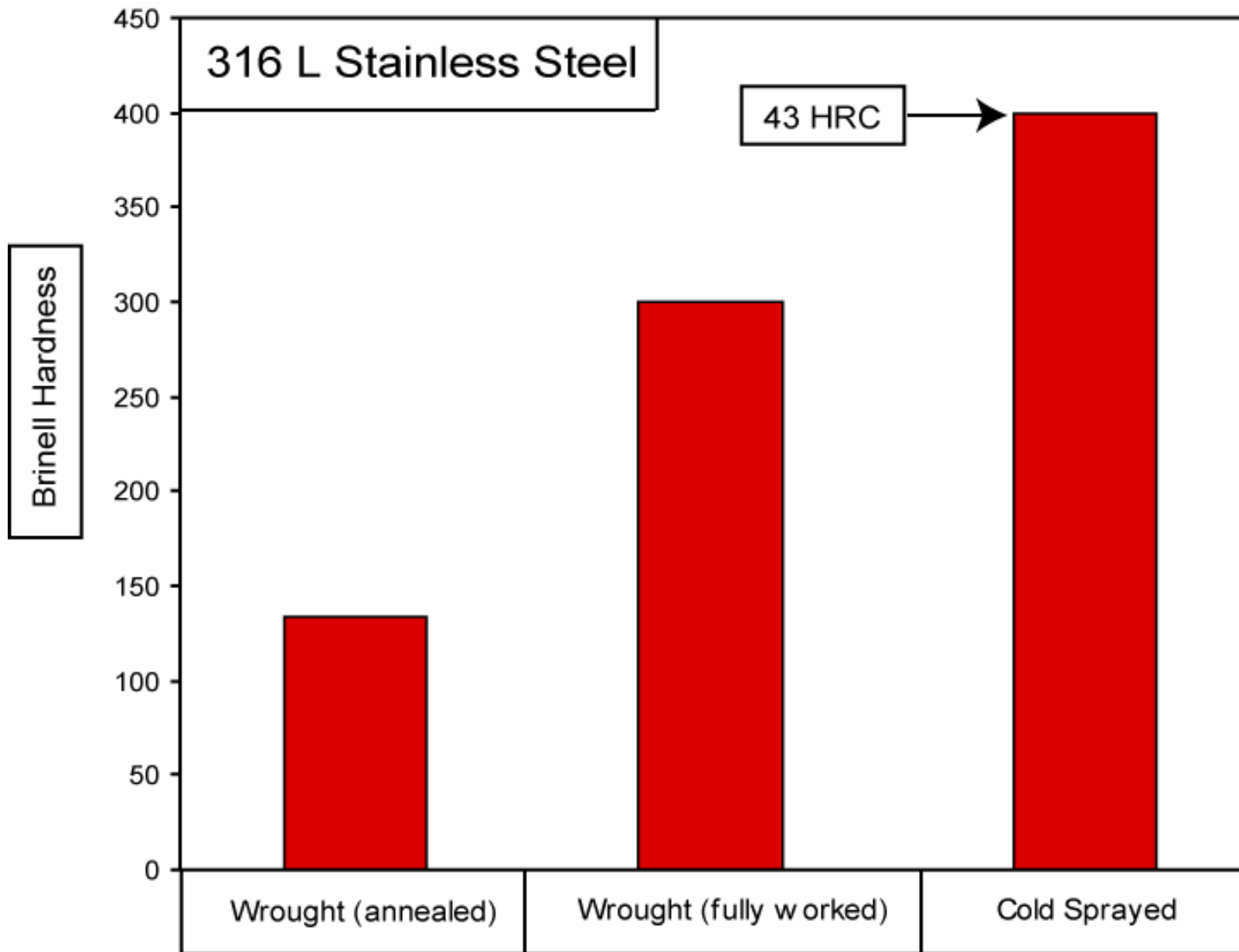


# Cold Sprayed vs. Wrought Materials: Hardness



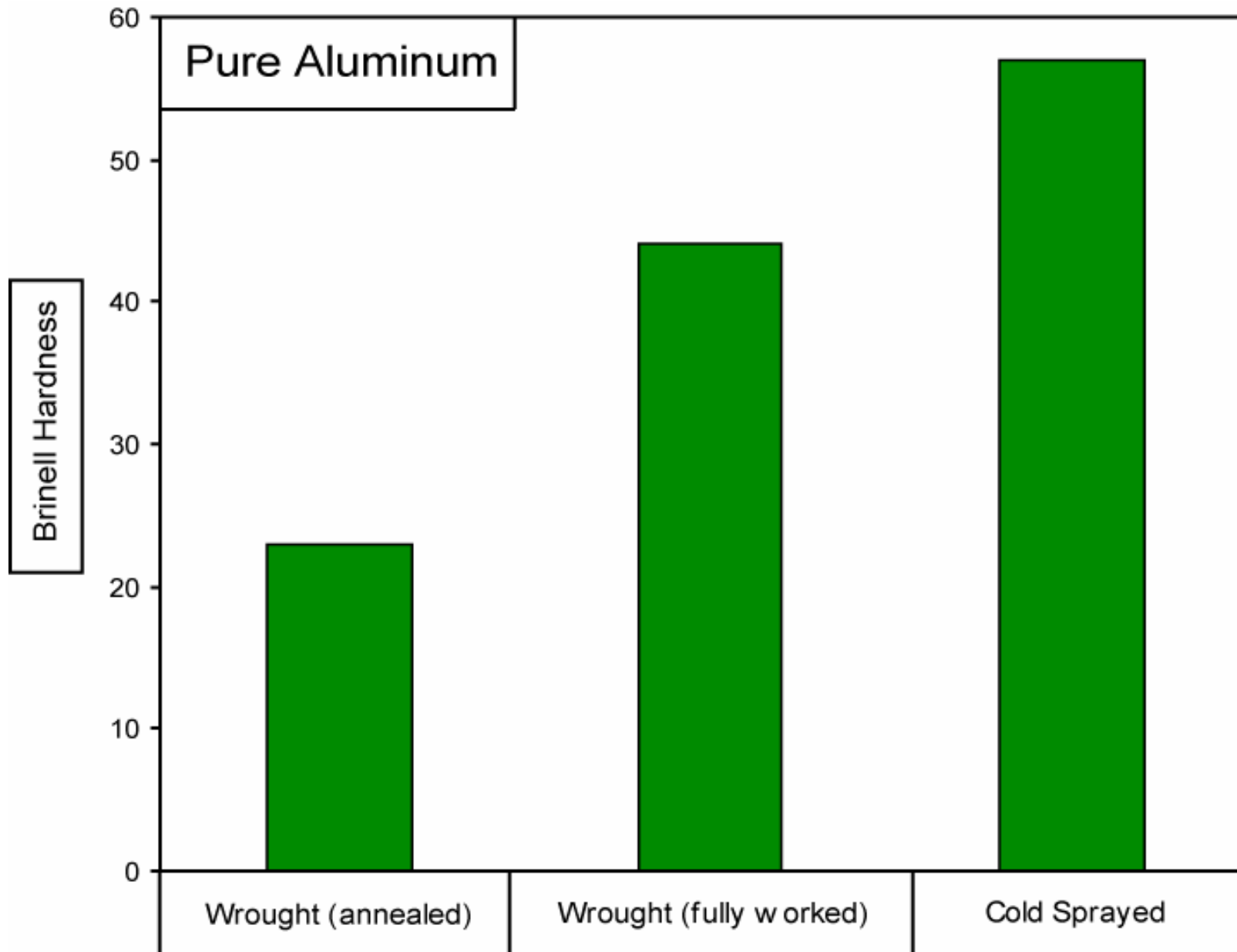


# Cold Sprayed vs. Wrought Materials: Hardness



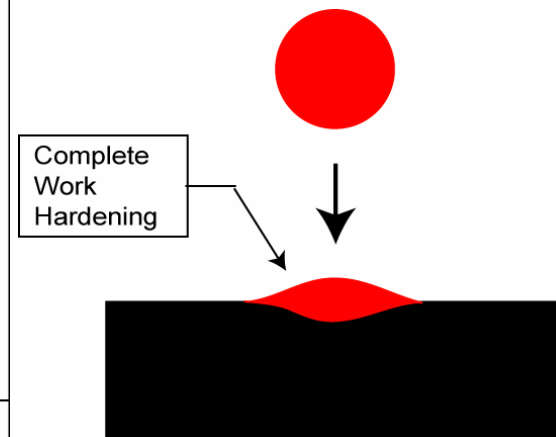
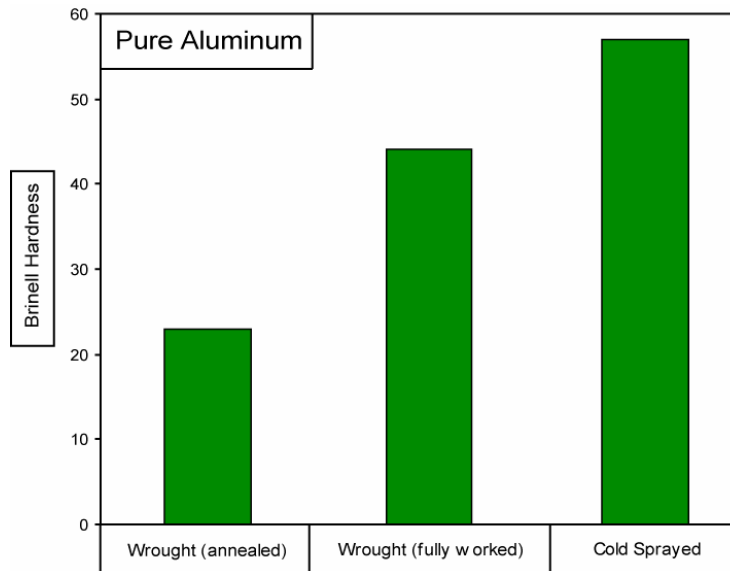
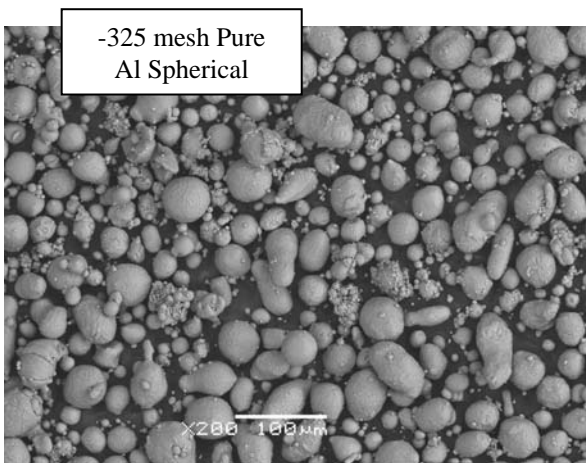
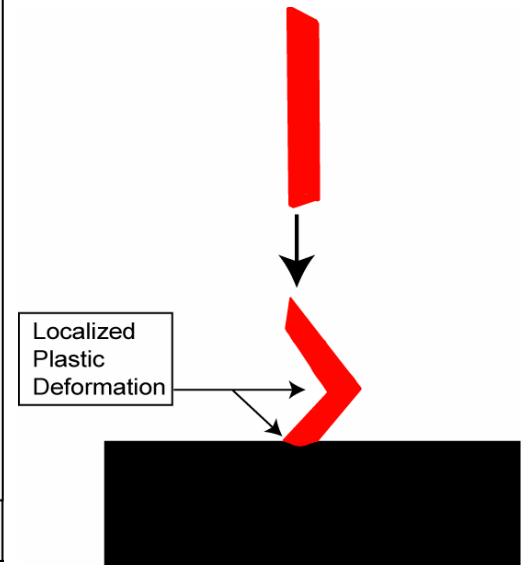
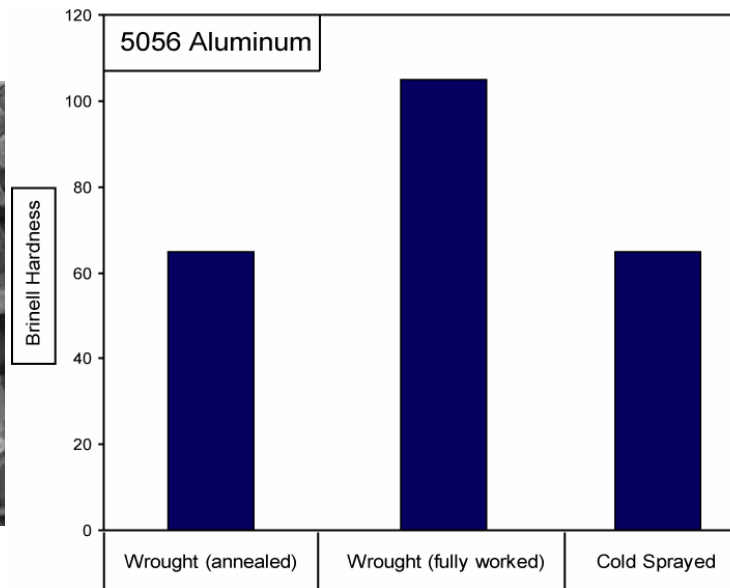
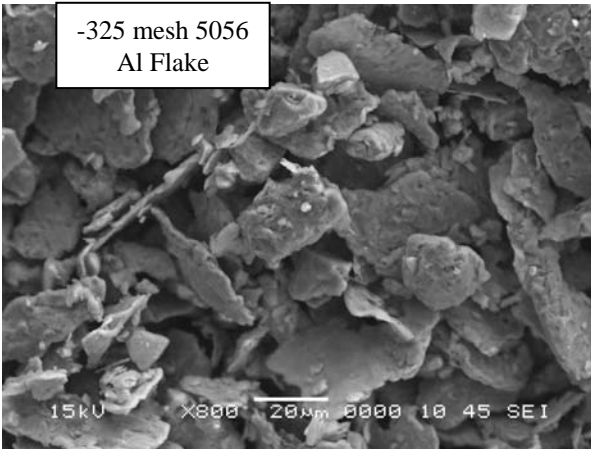


# Cold Sprayed vs. Wrought Materials: Hardness





# Aluminum Powder Morphology

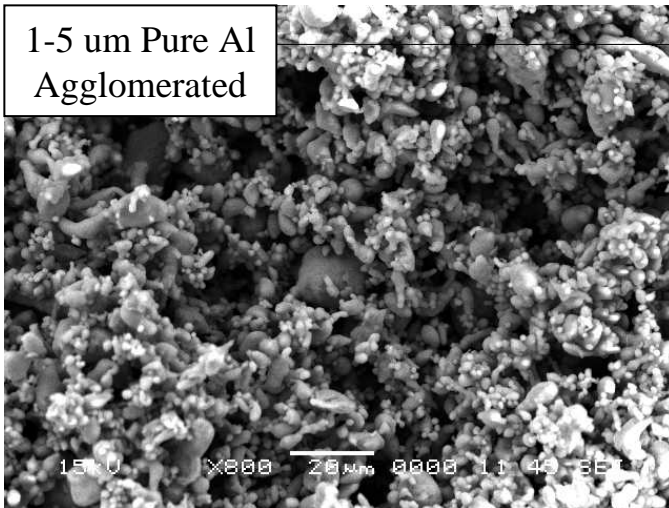




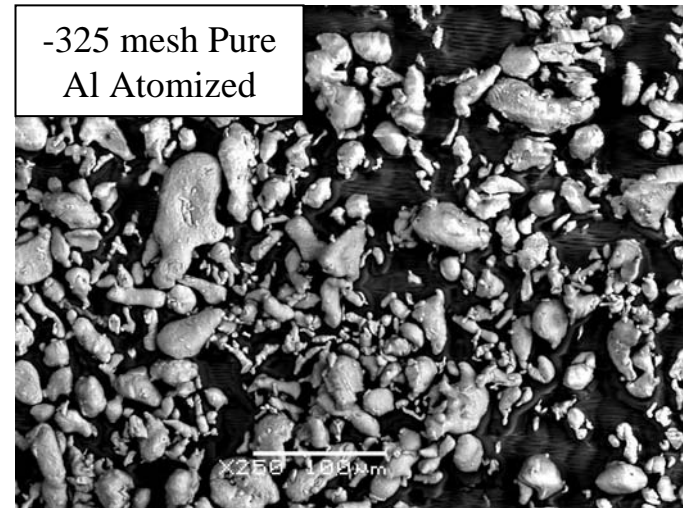
# Aluminum Powder Morphology



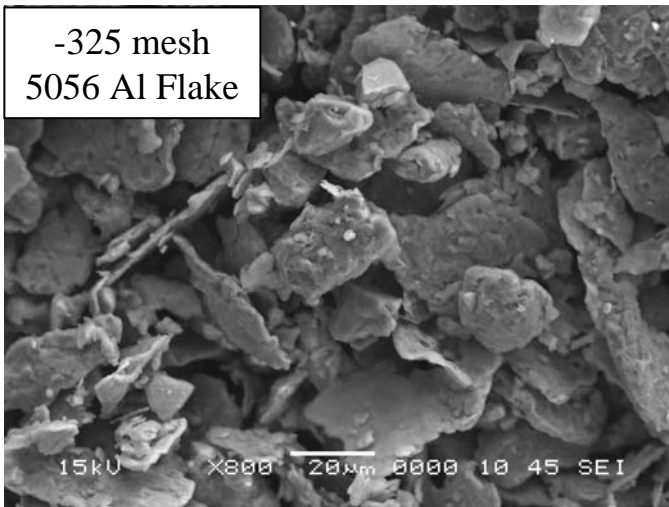
1-5  $\mu\text{m}$  Pure Al  
Agglomerated



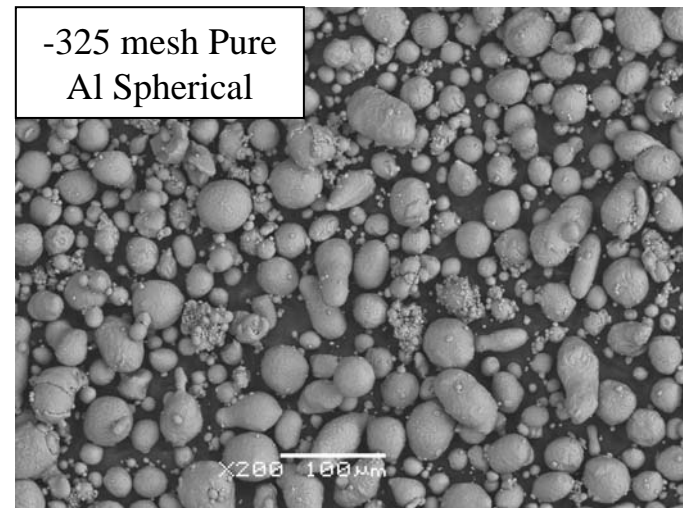
-325 mesh Pure Al  
Atomized



-325 mesh  
5056 Al Flake



-325 mesh Pure Al  
Spherical



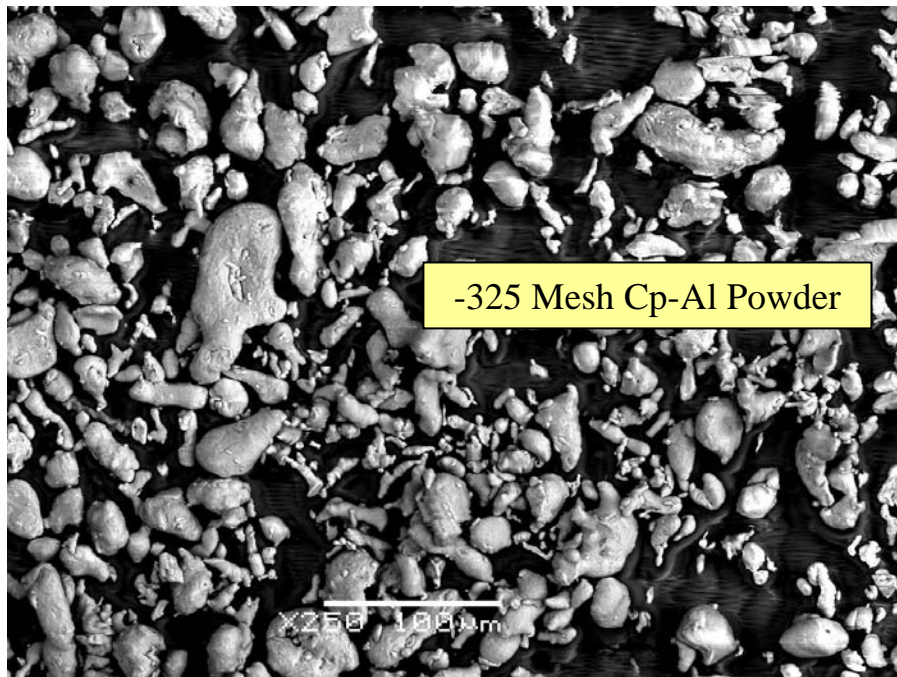
**Coating quality is critically dependent on the feed powder composition, morphology, oxygen content, and mechanical properties.**



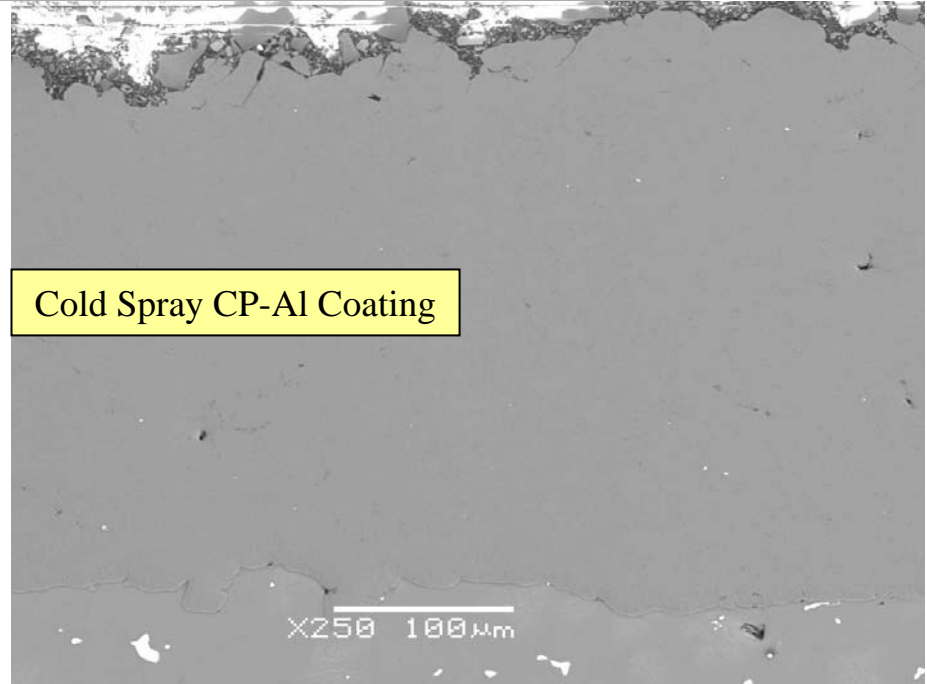


# Purity of Cold Sprayed Aluminum

Oxygen content measured by Inert Gas Fusion  
ASTM E 1019-03



-325 Mesh Cp-Al Powder



Cold Spray CP-Al Coating

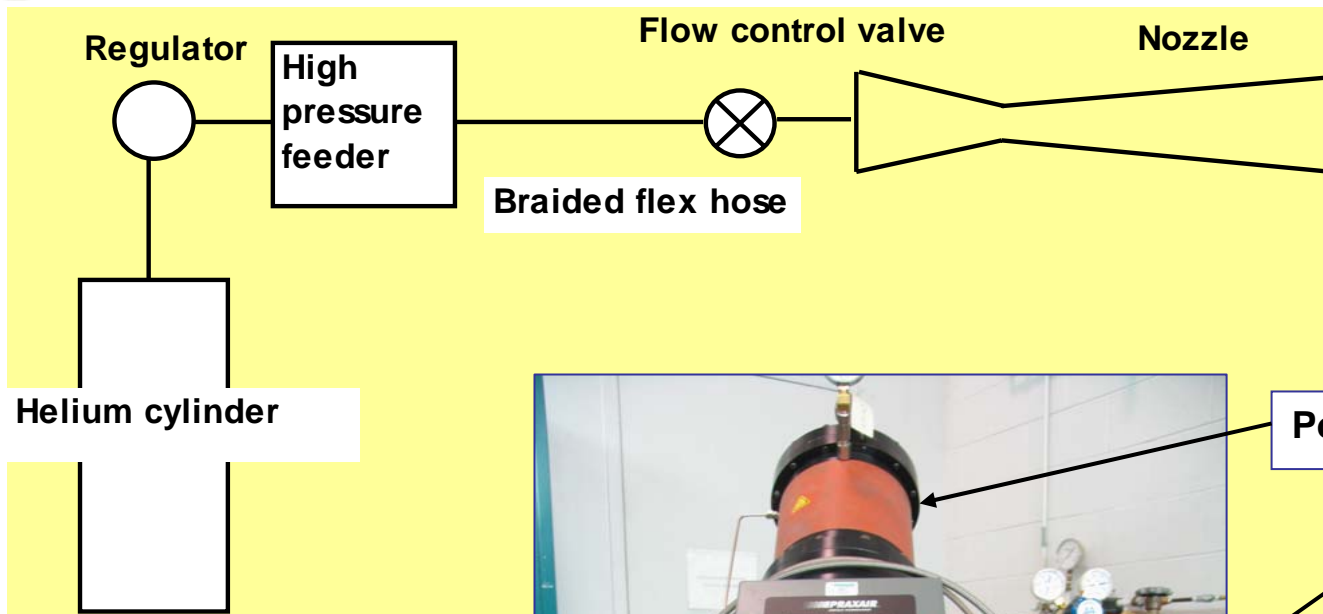
0.34 %Oxygen

0.25 %Oxygen

\*The oxygen content of the cold spray coating is largely determined by the oxygen content of the original powder, not the process.



# Portable ARL Cold Spray System



Powder Feeder

Helium Tank

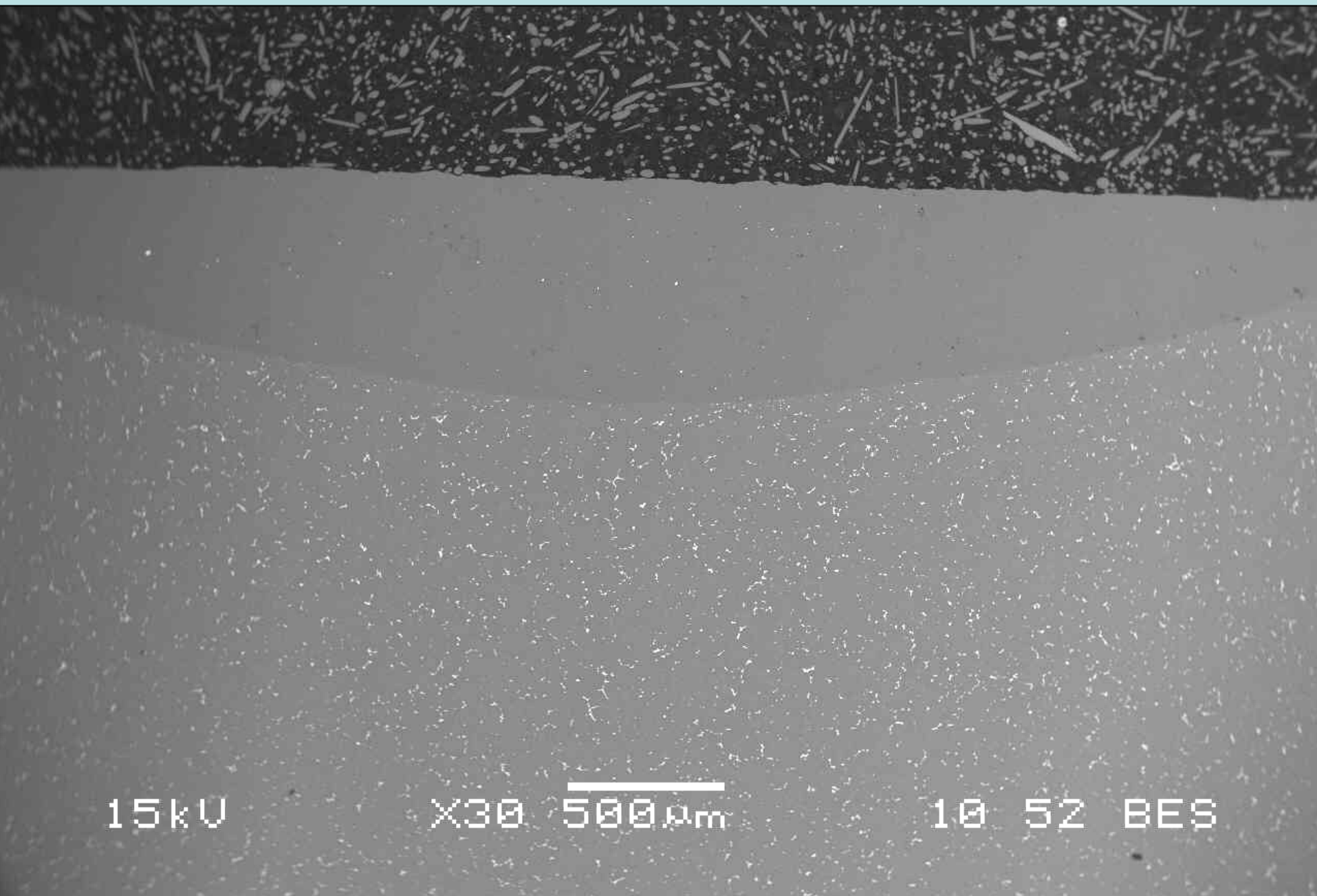
Spray Nozzle



# **ARL Portable System Parameters for Applying CP-Al to ZE41A - Mg**

<b>Operating Parameter</b>	<b>Setting</b>
<b>Helium Pressure</b>	<b>400 – 500 psi</b>
<b>Helium Temperature</b>	<b>20 Degree C</b>
<b>Helium Flow</b>	<b>20 SCFM</b>
<b>Powder Flow</b>	<b>1 – 5 gram/minute</b>
<b>Particle Mean Diameter</b>	<b>20 micron</b>
<b>Particle Exit Velocity</b>	<b>1000 meter/second</b>
<b>Helium Cylinder Life</b>	<b>9 minutes</b>

# CP-Al Deposited by the ARL Portable Cold Spray System



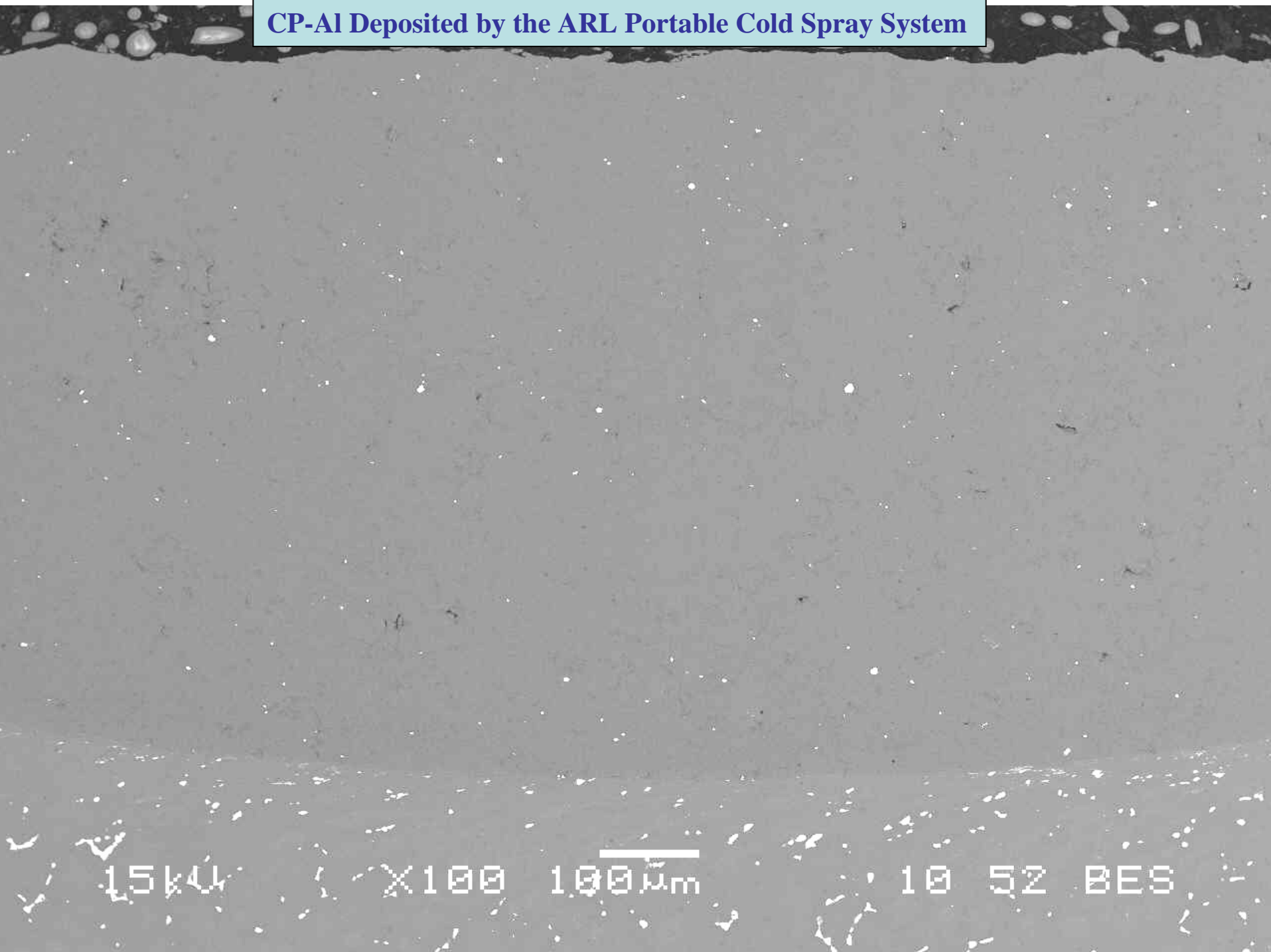
15kV

X30 500µm

10 52 BES



# CP-Al Deposited by the ARL Portable Cold Spray System



15kV

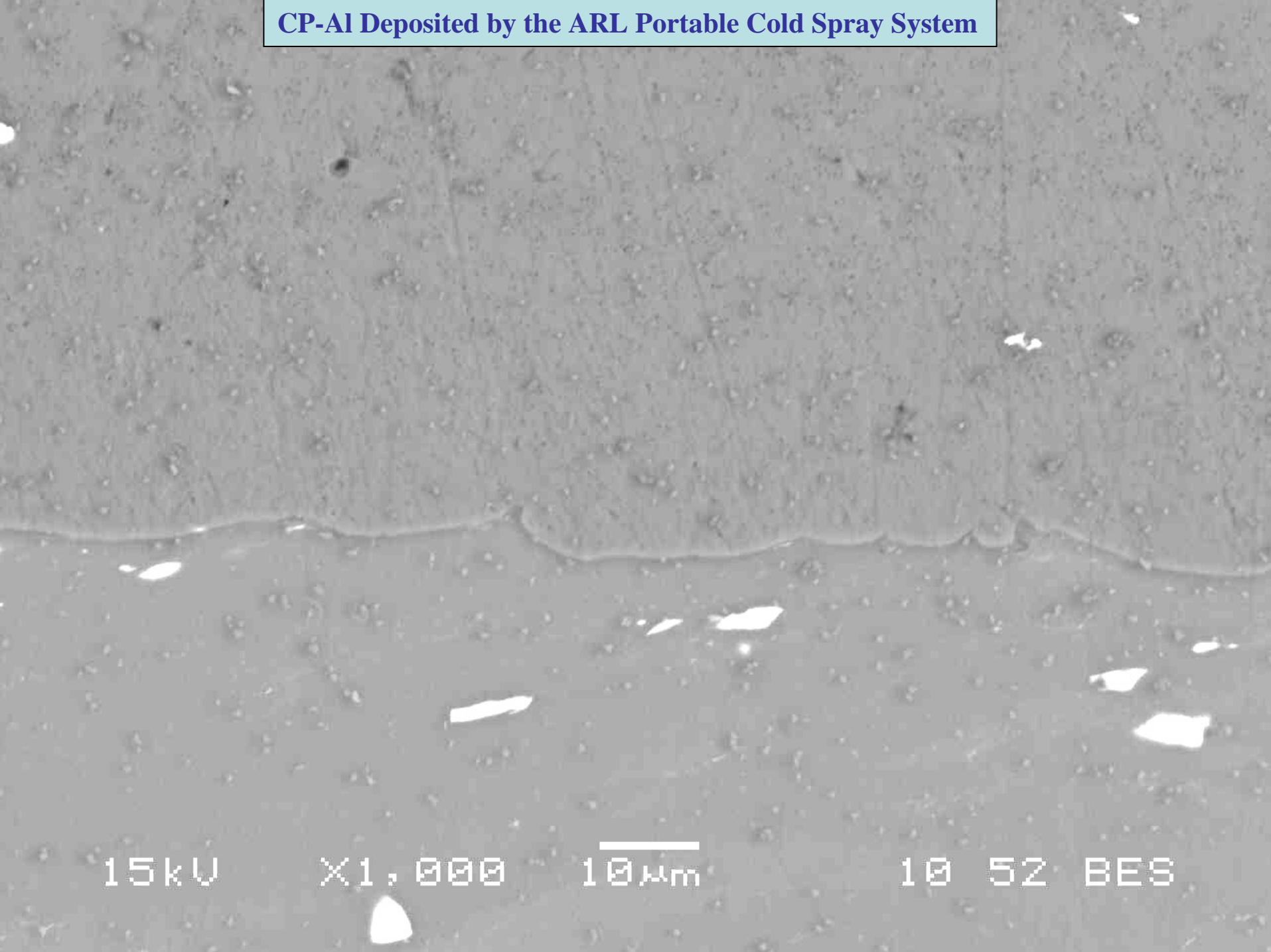
X100

100µm

10

52

BES



15kV

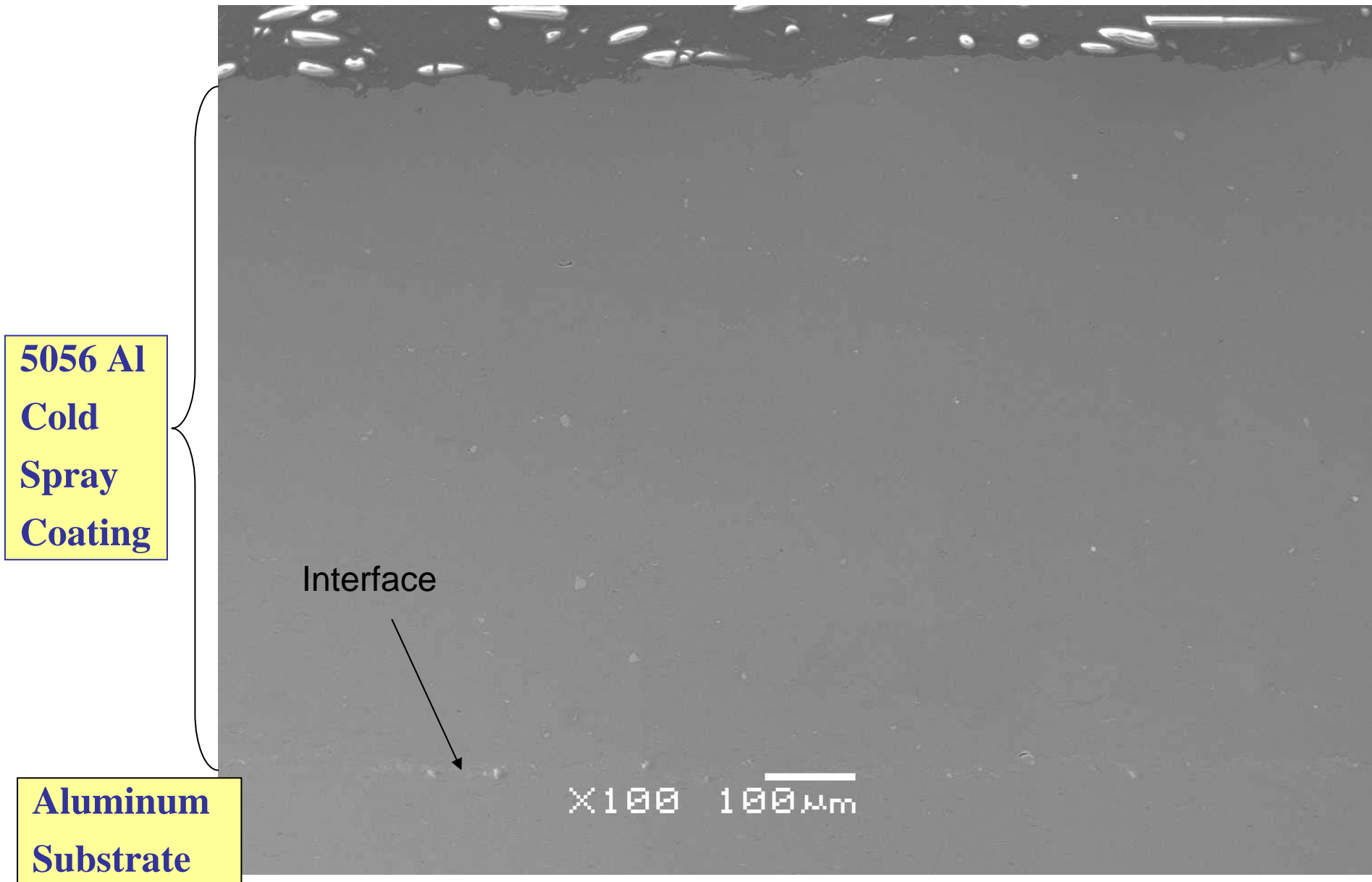
X1,000

10  $\mu$ m

10 52 BES



# 5056 Al Deposited by the Stationary System Using He



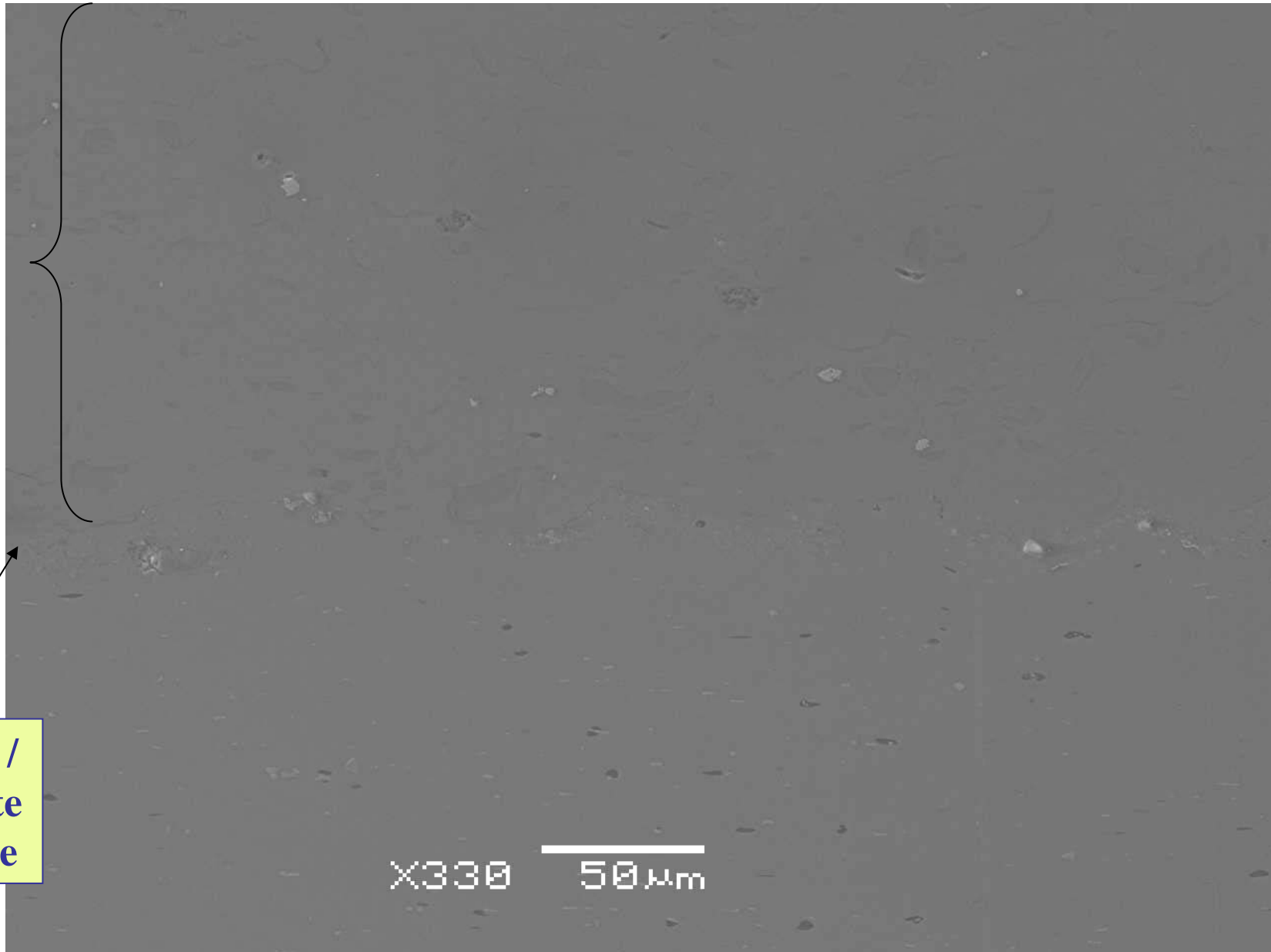


# 5056 Al Deposited by the Stationary System Using He

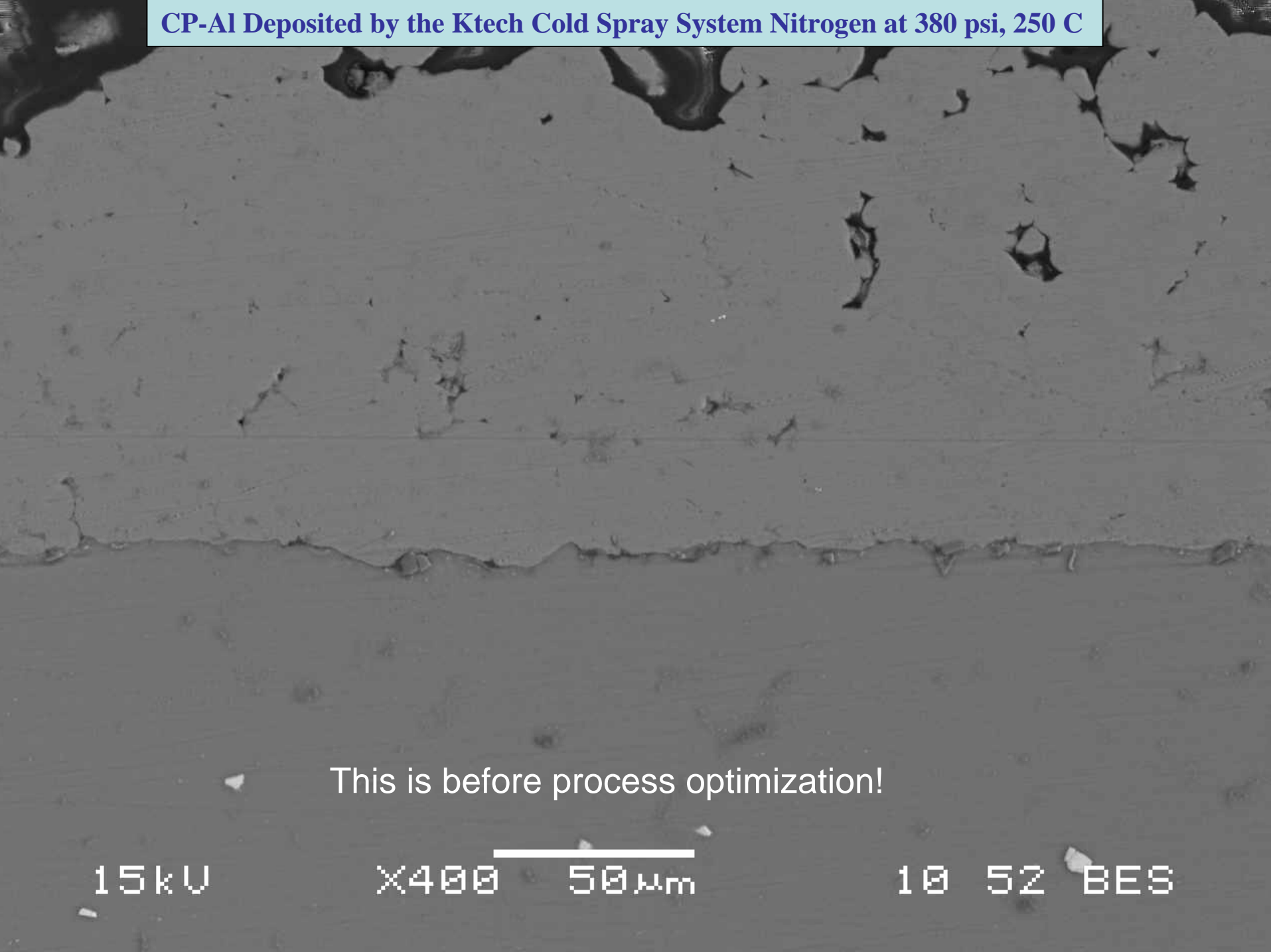


**Cold  
Spray  
5056  
Coating**

**Coating /  
Substrate  
Interface**







This is before process optimization!

15kV

X400 50µm

10 52 BES



# Applying CP-Al by Cold Spray over Magnesium



## ARL Achievements (FY07 Results Highlighted in Red)

### Corrosion Resistance:

- >5,000, **>7,000 hrs** salt fog resistance-ASTM B117 (Al, 4340 steel substrates)
- >619, **>1,000hrs** (ZE 41A magnesium substrate)

### Hardness:

57 Brinell Hardness

### Yield Strength:

22ksi comparable to ZE41A-T6 and AZ91E-T6 magnesium

### Density:

>99% with oxide content of 0.25%

### Adhesion:

> 8,500 psi, **>10,350 psi**

### Cold Spray Process Summary:

can be applied in production or in the field at room temperature

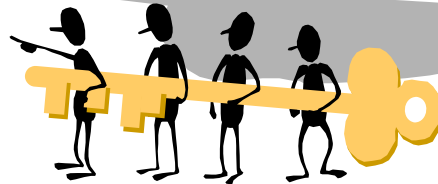
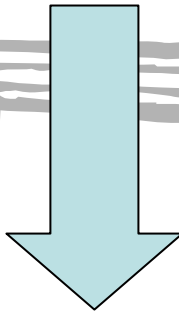


# ARL Technical Hurdle

: to achieve similar results with the use of nitrogen as the carrier gas

: this hurdle has been overcome in FY07 with the use of a plastic nozzle!

## Technical Approach



- \* nozzle design
- \* system modifications (heater, powder feed)
- \* powder morphology and condition





# Future Developments



## **Specification Development:**

Like to explore using Mantech program at ARL-PSU to create commercial specification for cold spray

## **Cold Spray Book:**

Published through the UK